AMPLITUDE ANOMALIES AT LASA

9 AUGUST 1967

REPORT No. LL- 7

Prepared for

LINCOLN LABORATORIES
MASSACHUSETTS INSTITUTE of TECHNOLOGY

EARTH SCIENCES
A TELEDYNE COMPANY

LL– 7

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Purchase Order No. BB-246

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FOREWORD

The work documented in this report is part of a study of the travel-time and amplitude anomalies observed at the Large Aperture Seismic Array (LASA) in Montana. This report supercedes Report No. LL-4 in that additional data and data quality control are used in this report.

The work was performed by the Applied Research Section, Earth Sciences, a Teledyne Company, 314 Montgomery Street, Alexandria, Virginia, under Lincoln Laboratory Contract No. BB-246.

This report was written by P. W. Broome, F. A. Klappenberger, D. E. Frankowski. Assistance was provided by A. L. Kurtz, V. R. McLamore, R. D. Mierley, P. A. Santiago, H. N. Johnson, and F. J. Whited. Dr. E. F. Chiburis served as a consultant. The project director was P. W. Broome.

ABSTRACT

Average amplitude anomalies are presented as functions of source region. Data from approximately 300 events were used in this analysis.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

1. INTRODUCTION

Observed short period teleseismic P-phase amplitudes vary greatly, even between seismometers that are relatively closely spaced. These variations exceed anything that can be easily attributed to instrumentation, radiation pattern effects, or obvious geologic factors. These variations have been termed "amplitude anomalies". By observing a large number of events, certain consistencies are found, in particular, some stations exhibit a preference for events from a given source region.

The object of this report is to define the LASA amplitude anomalies as functions of distance and azimuth to the source region. Statistical qualifications on the observed anomalies and on the data from approximately 300 events (Figure 1) which were used to derive these anomalies are also given.

2. PROCEDURE

2.1 Data Collection

Figure 2 shows a typical record of an event as seen on the LASA 16mm Develocorder film. Two such films record the earth motion at the center seismometer of each of the 21 LASA subarrays. The maximum P-wave amplitude and period within the first 3 or 4 seconds of the signal were measured and converted to ground motion*. Since all sensors do not re-

*The maximum P-wave amplitude is defined to be that phase which has the largest amplitude, on the average, for all recording seismometers.

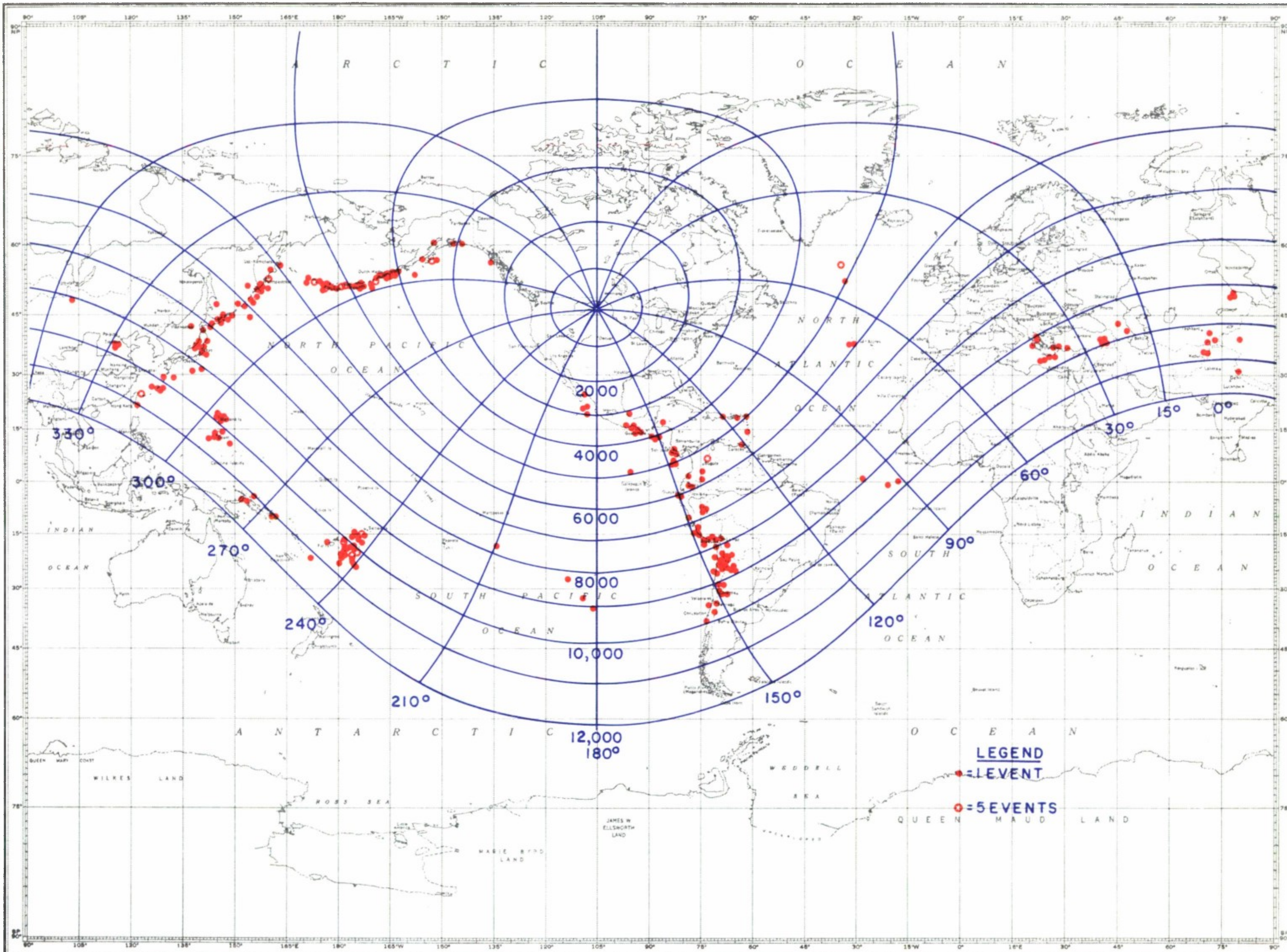


Figure 1. Event Location Chart with Distance-Azimuth Grid
(Distance in Kilometers, Azimuth in Degrees)

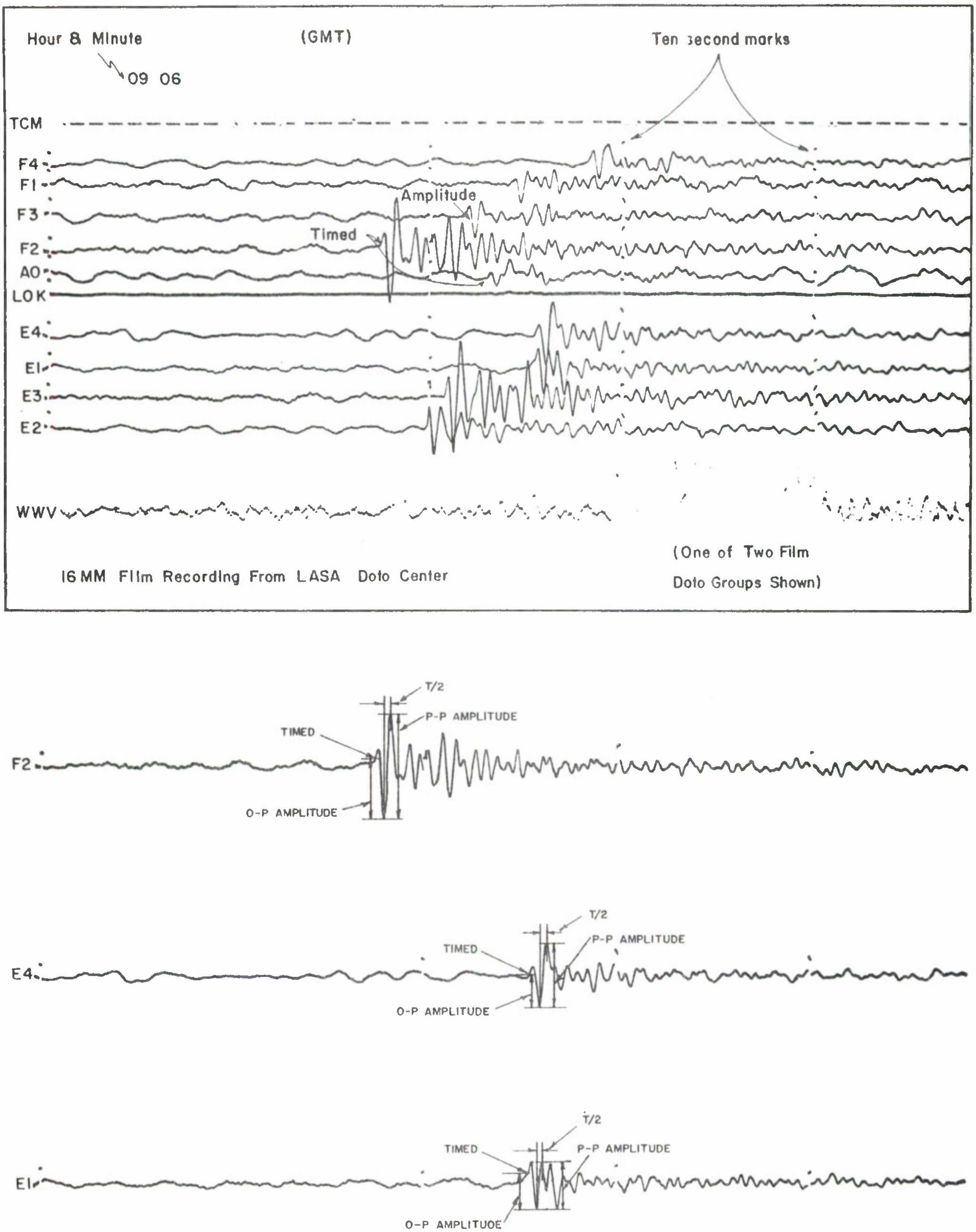


Figure 2. Typical Record Showing Amplitude Measurements

cord with the same signal-to-noise characteristics, each trace was given a quality grade by the analyst when read.

Quality Grade 1 = a perfect trace.

Quality Grade 2 = a trace on which the signal is easily read and has a similar shape (signature) to the other traces.

Quality Grade 3 = a trace on which the signal is seen but it is not distinct and/or has a markedly dissimilar signature to the other traces.

Quality Grade 4 = a trace on which the signal can not be seen.

In this report all but Grade 4 data were used. These data were then keypunched on IBM cards as shown in Figure 3 for use in further processings.

2.2 Data Reduction

In order to compare data from different events, it was first necessary to remove the effect of the sources on the received amplitudes. In doing this, we have assumed that the aperture of LASA is small compared to any lobe structure in the radiation pattern, and thus that all seismometers were sampling the same radiation field. The normalization method which we used was to normalize the amplitude at each station for each event to the geometric mean of the recorded amplitudes for that event. Thus if Y_{ij} and L_{ij} are the normalized and observed amplitudes for event i and station j respectively and N is the total number of observed amplitudes for event i, then

$$Y_{ij} = \frac{L_{ij}}{\left(\prod_{j=1}^{N} L_{ij}\right)^{1/N}} .$$

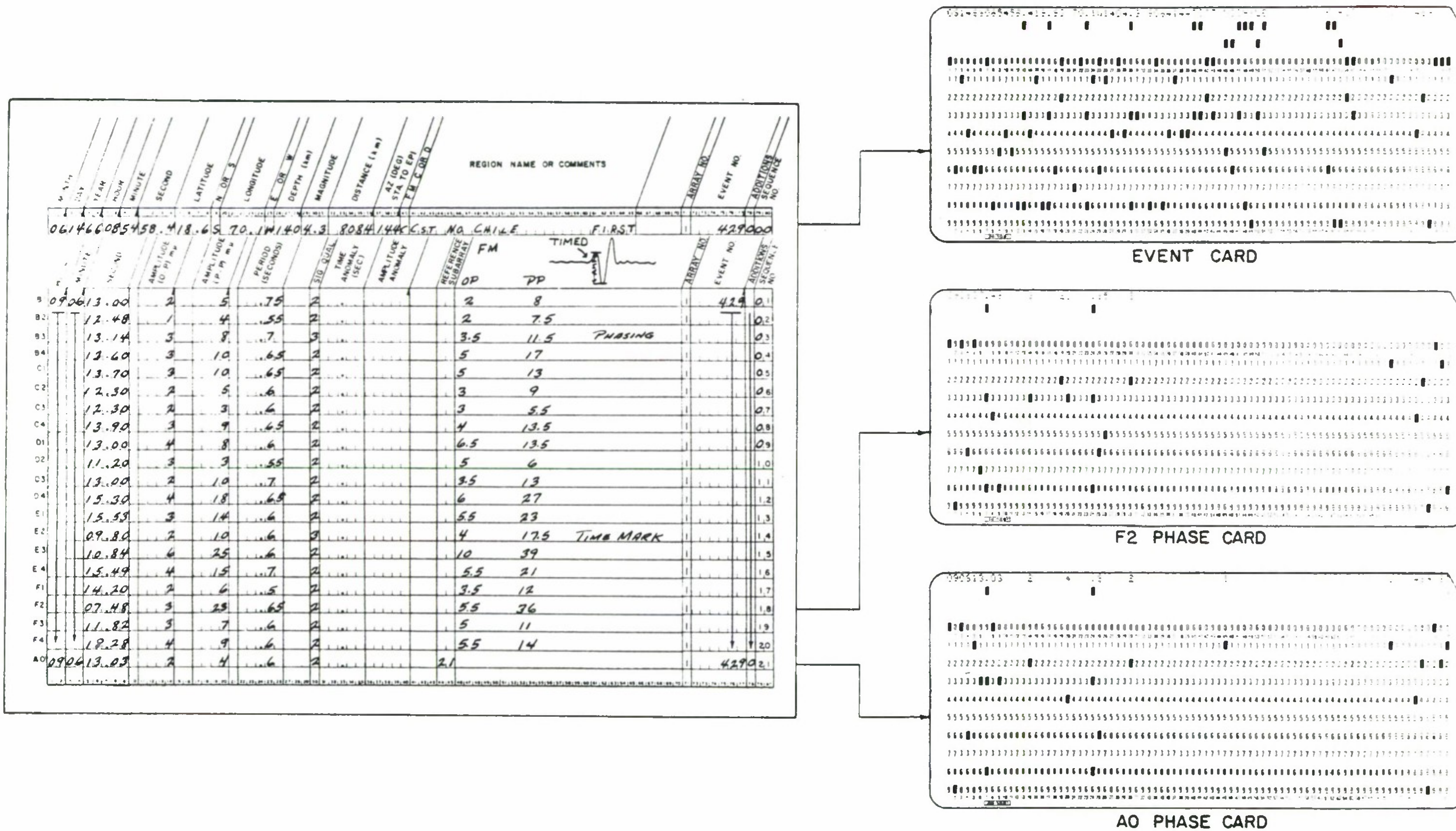


Figure 3. Analyst's Observations Sheet and Key Punched Data

The derivation and rationalization of this normalization method is given in Appendix A.

A computer program was used to normalize amplitudes for each event*. A sample output from this program is shown in Figure 4. (Additional data computed in the program are also shown.)

2.3 Data Display

The events were grouped into cells by distance and azimuth. With the assumption that the amplitude anomaly within each cell is constant, a computer program was used to compute the geometric mean of the normalized amplitudes for each station **. The program also computed a measure of the deviation about the estimated mean as well as the number of events recorded for each station and cell***.

Figure 5 shows a sample of this information as the computer output listing with appropriate descriptions added. The data for all cells and subarrays are presented in Figures 6 through 26.

3. ERROR DETECTION

Using the assumption that the true amplitude anomalies are constant within geographic cells, it is possible to examine the scatter of the normalized amplitudes in each cell for the purpose of detecting errors due to blunders in data handling (and other possible sources of error). To detect and eliminate the scatter due to these human errors, the error model study described in Appendix D was undertaken. The results of this study indicate that the signal model is essentially of the form $L_{ij} = S_i g_j e_{ij}$, where L_{ij} is the observed

* A description of program "ANOMALY" is given in Appendix B

** Appendix A

*** A description of program "DISPLAY" is given in Appendix C

JUN 15 66 23/25/27.3 44.20N 149.10E 40KM DEEP, 4.9MAG. 7535KM DIST, 311DEG.AZ. A0 CKURILE 4310

OBSERVED DATA, EARTH MOTION IN MILLIMICRONS — COMPUTED ANOMALY DATA, RELATIVE TO A0 OR NORMALIZED TO THE AVERAGE

HR MIN SEC.	ZERO TO PEAK AMP	PEAK TO PEAK AMP	PERIOD (SEC.)	QUAL-ITY	TIME RSDL DIFFERANCE	Z TO P GEOMEAN	P TO P GEOMEAN	Z TO P AVERAGE	P TO P AVERAGE	IN-DEX	OBS. TIME	J.B. TIME	DIST DEG
23 36 24.69	14.0	22.0	.95	2	-.07	.67	.55	.60	.50	1	657.4	655.8	67.79
23 36 25.03	26.0	45.0	1.00	2	.01	1.25	1.13	1.12	1.03	2	657.7	656.1	67.83
23 36 24.45	27.0	51.0	1.00	2	.04	1.29	1.28	1.16	1.16	3	657.2	655.5	67.73
23 36 0	-0	-0	0	-4	0	0	0	0	0	4	632.7	655.2	67.70
23 36 24.14	32.0	70.0	1.30	3	-.14	1.53	1.76	1.38	1.60	5	656.8	655.3	67.71
23 36 25.26	16.0	30.0	.95	3	-.10	.77	.76	.69	.68	6	658.0	656.4	67.89
23 36 25.00	26.0	48.0	.90	2	.02	1.25	1.21	1.12	1.10	7	657.7	656.0	67.83
23 36 23.91	-0	-0	.90	2	-.00	0	0	0	0	8	656.6	655.0	67.65
23 36 24.80	30.0	59.0	1.00	3	-.25	1.44	1.49	1.29	1.35	9	657.5	656.1	67.84
23 36 25.90	24.0	45.0	1.00	-2	-.15	1.15	1.13	1.04	1.03	10	658.6	657.1	68.00
23 36 24.30	14.0	30.0	1.00	-2	-.03	.67	.76	.60	.68	11	657.0	655.4	67.72
23 36 23.04	50.0	90.0	.95	2	.01	2.40	2.27	2.16	2.05	12	655.7	654.1	67.51
23 36 22.88	6.0	13.0	.80	3	-.29	.29	.33	.26	.30	13	655.6	654.2	67.54
23 36 28.05	26.0	44.0	.95	-2	-.04	1.25	1.11	1.12	1.00	14	660.8	659.1	68.32
23 36 26.25	14.0	24.0	1.00	3	-.22	.67	.60	.60	.55	15	659.0	657.5	68.06
23 36 22.20	36.0	63.0	.95	-2	.16	1.72	1.59	1.55	1.44	16	654.9	653.1	67.36
23 36 24.80	-0	-0	0	3	-.30	0	0	0	0	17	657.5	656.1	67.84
23 36 29.77	17.0	38.0	1.10	3	-.43	.81	.96	.73	.87	18	662.5	661.2	68.66
23 36 0	-0	-0	0	-4	0	0	0	0	0	19	632.7	655.8	67.79
23 36 19.02	14.0	29.0	.90	-2	-.25	.67	.73	.60	.66	20	651.7	650.3	66.92
23 36 24.60	22.0	44.0	1.10	2	0	1.05	1.11	.95	1.00	21	657.3	655.6	67.76

JUN 17 66 6/50/25.0 18.60S 178.20W 479KM DEEP, 4.4MAG. 10186KM DIST. 244DEG.AZ. A0 CFIJI 4320

USC&GS SOURCE DATA

EVENT NUMBER

ARRIVAL TIME	ZERO-TO-PEAK AMPLITUDE	PEAK-TO-PEAK AMPLITUDE	PERIOD OF MAXIMUM AMPLITUDE PHASE	QUALITY GRADE	COMPUTED TIME ANOMALY	ZERO-TO-PEAK AMPLITUDES NORMALIZED TO GEOMETRIC MEAN	PEAK-TO-PEAK AMPLITUDES NORMALIZED TO GEOMETRIC MEAN	ZERO-TO-PEAK AMPLITUDES NORMALIZED TO ARITHMETIC MEAN	PEAK-TO-PEAK AMPLITUDES NORMALIZED TO ARITHMETIC MEAN	SUBARRAY NUMBER	OBSERVED TRAVEL-TIME	J.B. TRAVEL-TIME	EPICENTRAL DISTANCE
7 2 43.30	8.0	[illegible]	[illegible]	2	-.08	1.05	1.05	.99	1.00	1	738.3	736.5	91.71
7 2 42.72	7.0	10.0	.80	2	-.22	.92	.81	.86	.77	2	737.7	736.0	91.61
7 2 42.45	7.0	11.0	.75	2	-.10	.92	.89	.85	.84	3	737.4	735.6	91.53
7 2 43.04	-0	-0	.90	2	.06	0	0	[illegible]	0	4	738.0	736.1	91.62
7 2 43.45	10.0	15.0	.90	2	.00	[illegible]	[illegible]	[illegible]	[illegible]	5	[illegible]	736.5	[illegible]
7 2 43.16	4.0	8.0	.90	2	-.28	[illegible]	[illegible]	[illegible]	[illegible]	6	[illegible]	[illegible]	[illegible]
7 2 42.40	11.0	19.0	[illegible]	2	-.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7 2 [illegible]	16.0	23.0	[illegible]	3	-.05	[illegible]	[illegible]	[illegible]	[illegible]	16	[illegible]	[illegible]	[illegible]
7 2 47.10	5.0	13.0	[illegible]	2	-.06	[illegible]	[illegible]	[illegible]	[illegible]	17	[illegible]	740.2	[illegible]
7 2 42.76	6.0	12.0	.80	2	-.71	[illegible]	[illegible]	[illegible]	.92	18	737.8	736.6	91.73
7 2 38.69	11.0	13.0	.80	2	-.29	1.45	1.05	1.36	1.00	19	733.7	732.1	90.75
7 2 41.49	10.0	15.0	1.00	3	-.79	1.32	1.21	1.23	1.15	20	736.5	735.4	91.47
7 2 42.88	10.0	15.0	.80	2	0	1.32	1.21	1.23	1.15	21	737.9	736.0	91.60

Figure 4. Sample Output from Program "ANOMALY"

PAGE NO. 18 SUBARRAY OR SENSOR NO. = 18

CENTER DISTANCE

CENTER AZIMUTHS

MEAN

STANDARD DEVIATION

NO. OF EVENTS USED

	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	10000	10500	11000
	0	0	0	0	0	0	0	0	0	0	0	0	0	1.41	0	.72	.75
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.21	.34
	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2
	0	0	0	0	1.17	0	0	0	0	0	0	0	.59	.37	.62	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	.40	0	.47	0	0
	0	0	0	0	1	0	0	0	0	0	0	0	2	1	4	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	.50	1.20	0	0	0	0	0	0	.70	.97	1.04	0	0
105	0	0	0	0	0	.57	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	1	2	0	0	0	0	0	0	1	1	1	0	0
	0	0	1.21	0	1.62	1.54	1.36	1.78	1.19	1.33	2.09	2.02	1.59	2.26	0	0	0
135	0	0	0	0	.43	.16	.51	0	.05	.53	.43	.24	.08	.13	0	0	0
	0	0	1	0	5	4	3	1	2	4	5	7	3	3	0	0	0
	0	1.22	1.75	0	1.02	0	0	0	0	0	0	0	0	1.09	1.43	0	0
165	0	.32	.27	0	0	0	0	0	0	0	0	0	0	.54	0	0	0
	0	3	3	0	1	0	0	0	0	0	0	0	0	3	1	0	0
	.67	0	0	0	0	0	0	0	0	0	1.41	0	1.85	0	0	0	0
195	.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.83	1.21	0
225	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.07	.44	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	1.07	.86	1.26	.83
255	0	0	0	0	0	0	0	0	0	0	0	0	0	.27	.22	.29	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	6	14	8	1
	0	0	0	0	0	0	0	0	0	0	0	0	0	.57	1.19	.89	0
285	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.05	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	0
	0	.97	.96	1.19	.90	.96	1.07	.99	.78	.85	.97	.99	0	0	1.20	1.30	0
315	0	.32	.17	.37	.33	.20	0	.25	.25	.24	.29	.08	0	0	.29	.62	0
	0	5	2	5	7	9	1	4	4	6	2	5	0	0	3	4	0
	0	0	0	0	0	.91	0	0	0	0	0	0	0	1.37	0	0	0
345	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0

Figure 5. Sample Output of Program "DISPLAY"

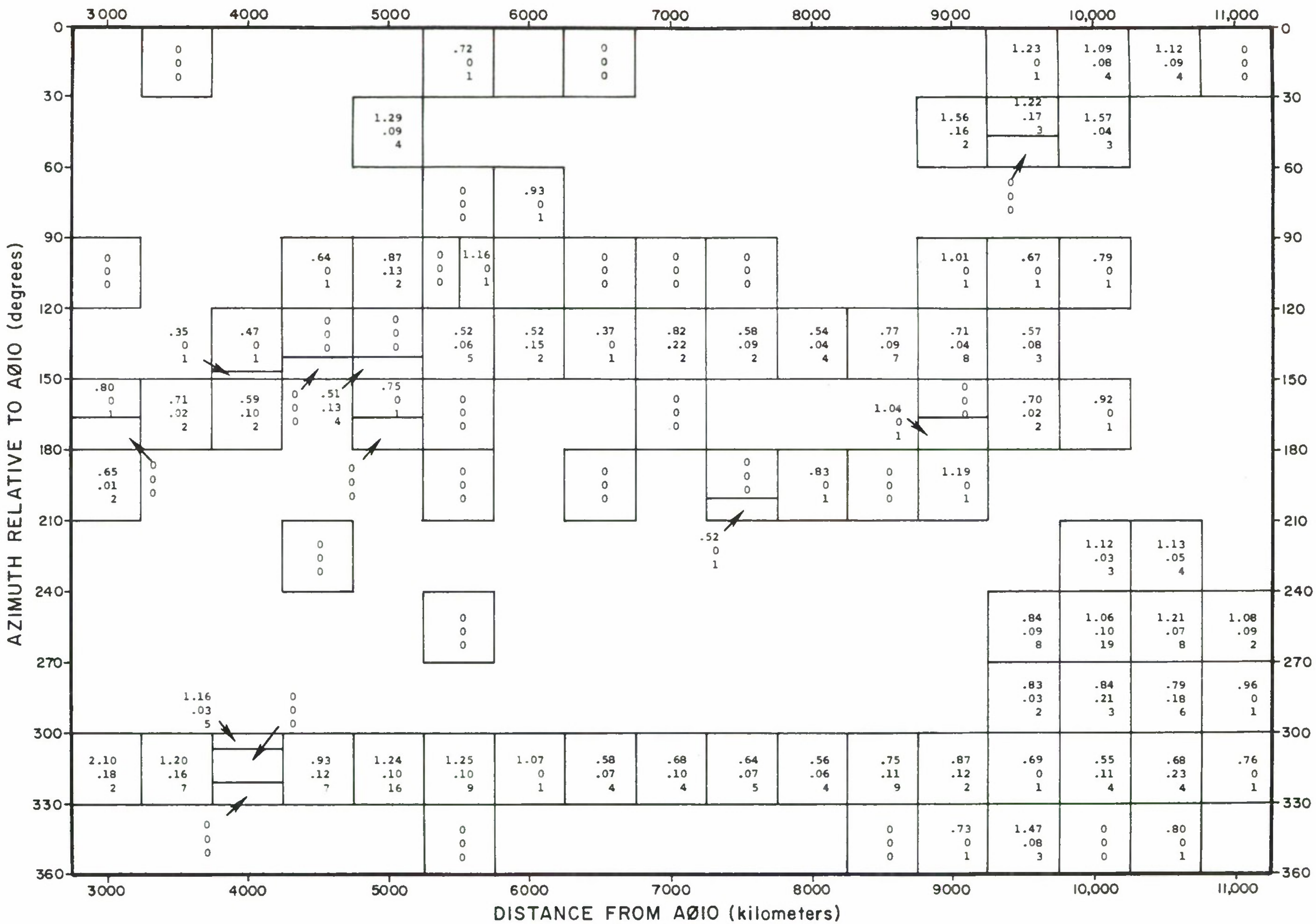


Figure 6. Subarray B1

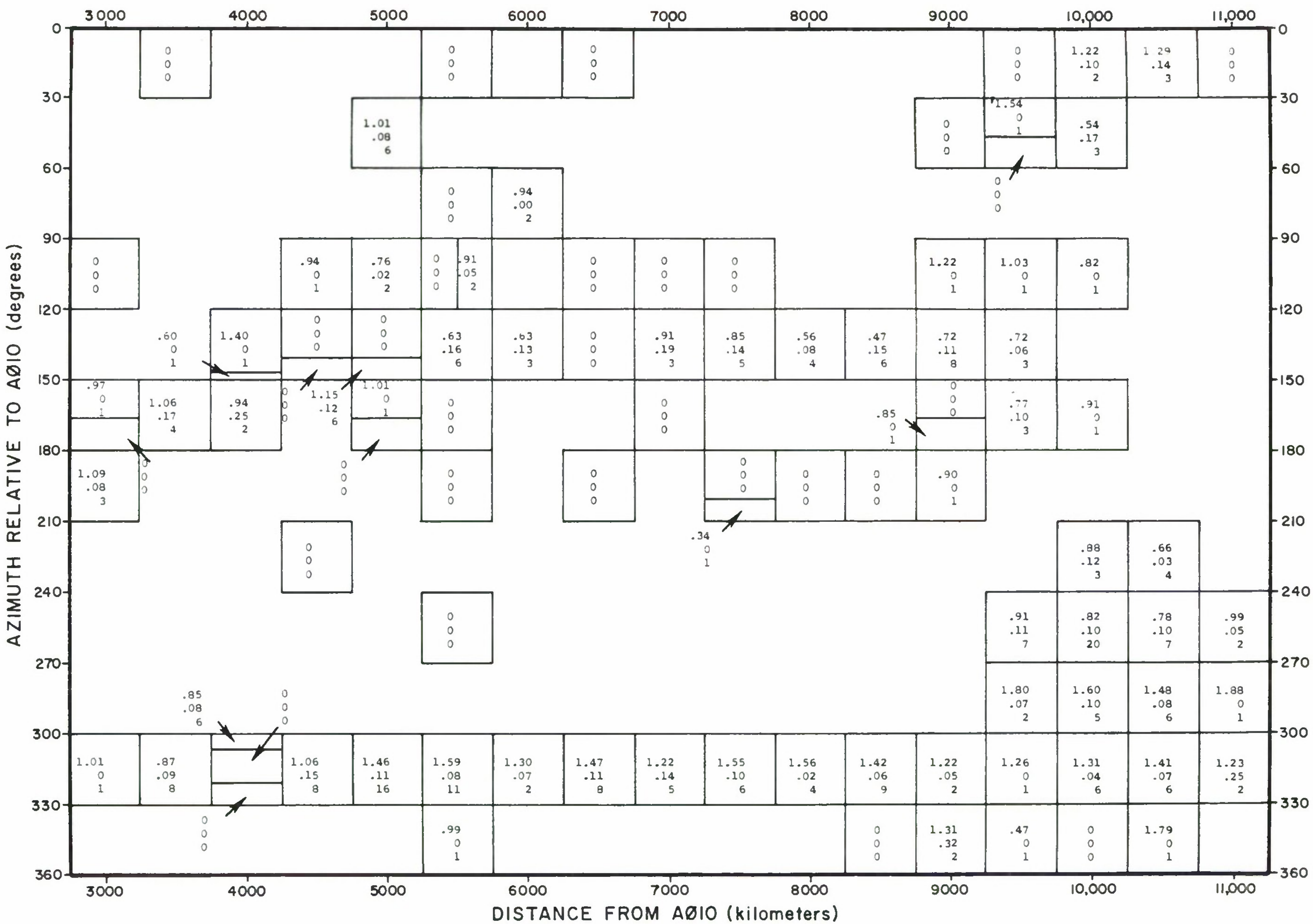


Figure 7. Subarray B2

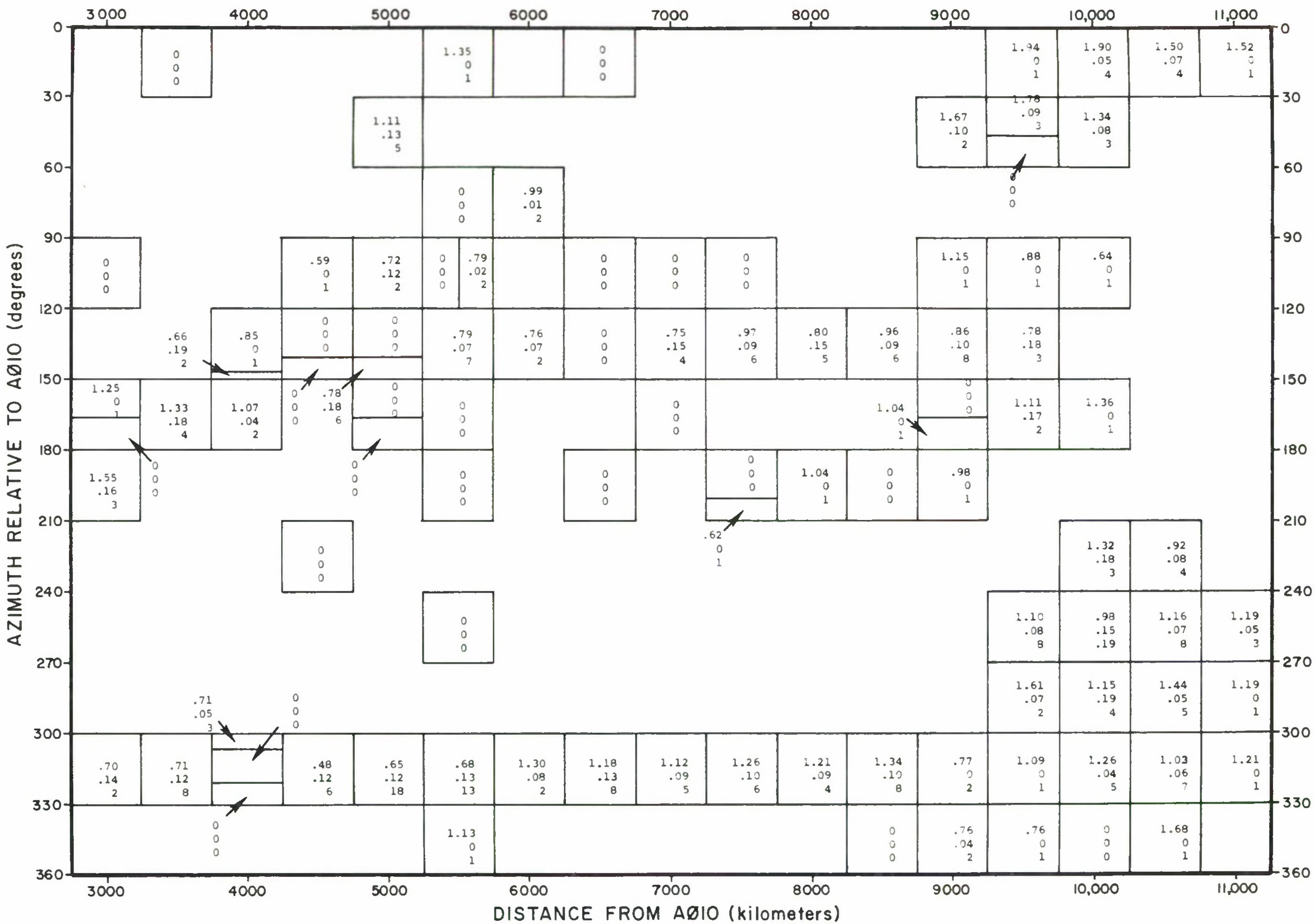


Figure 8. Subarray B3

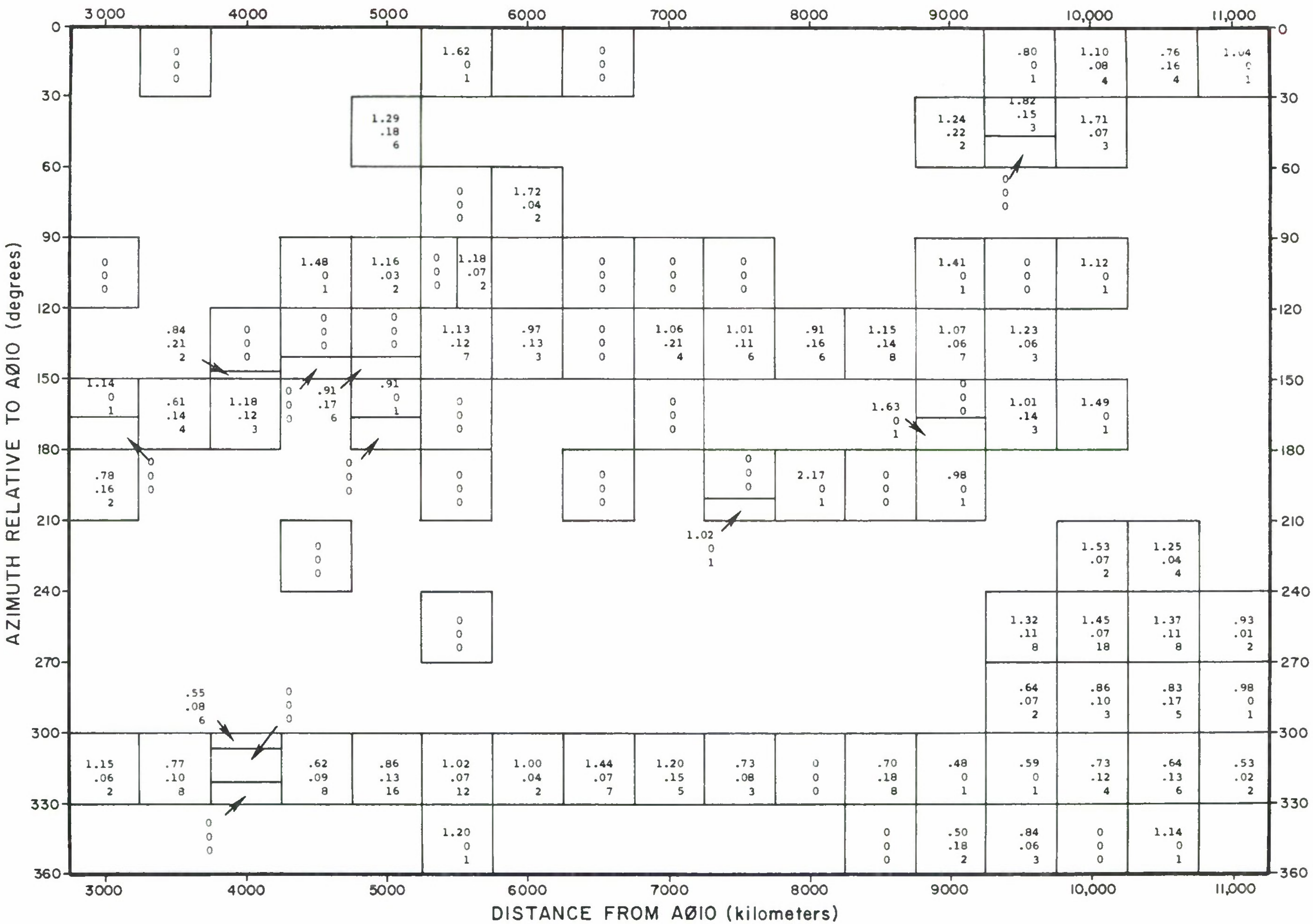


Figure 9. Subarray B4

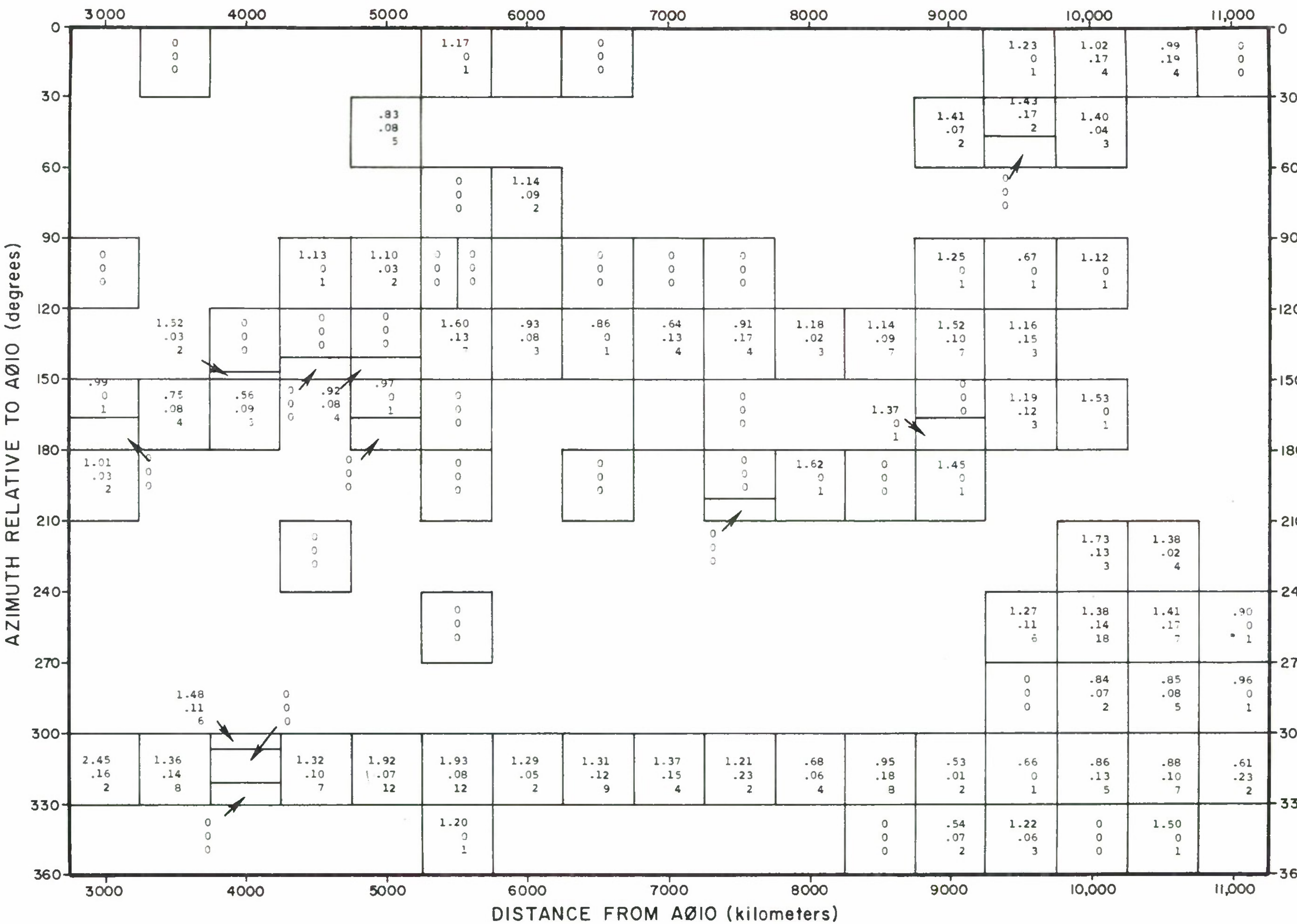


Figure 10. Subarray C1

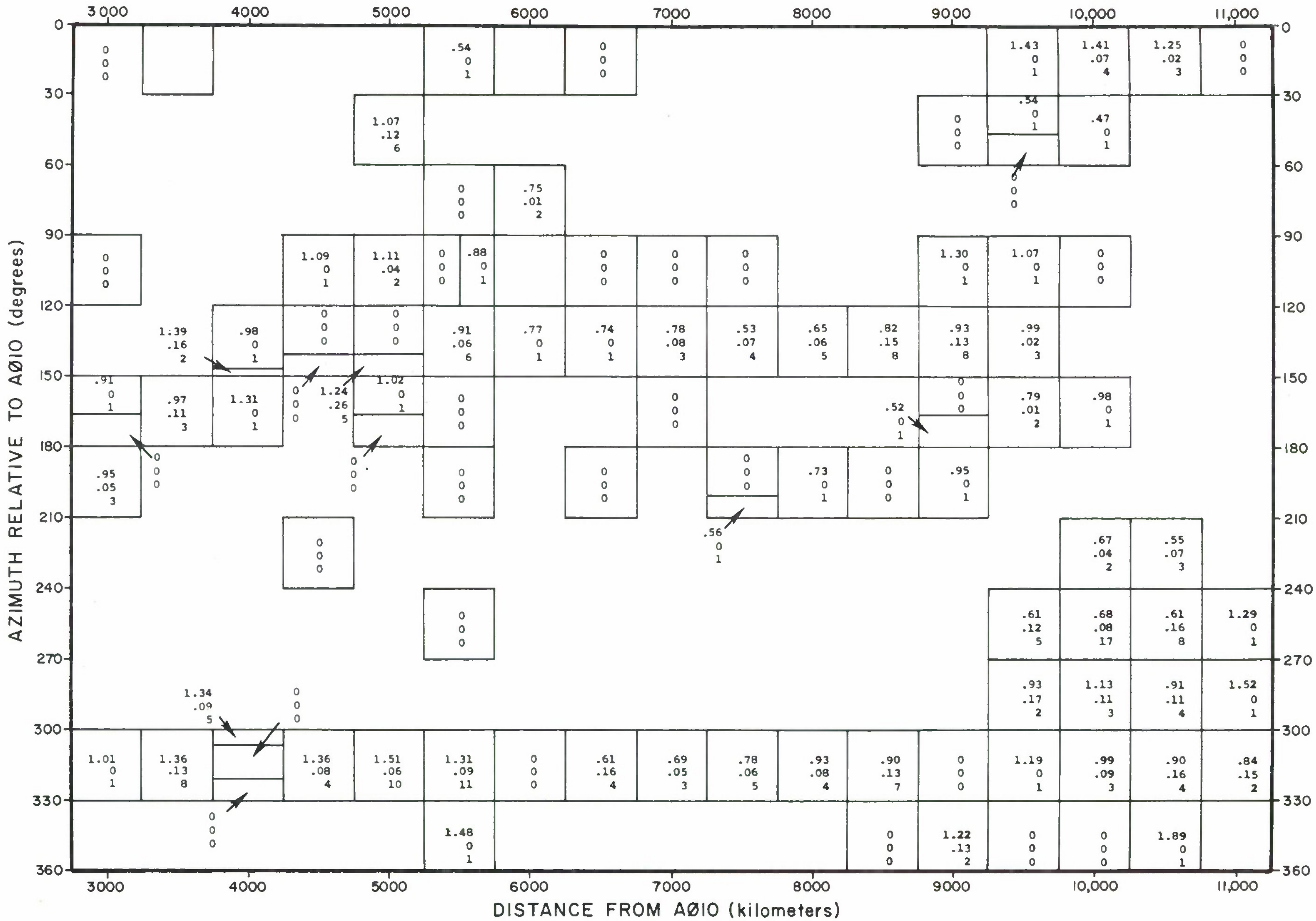


Figure 11. Subarray C2

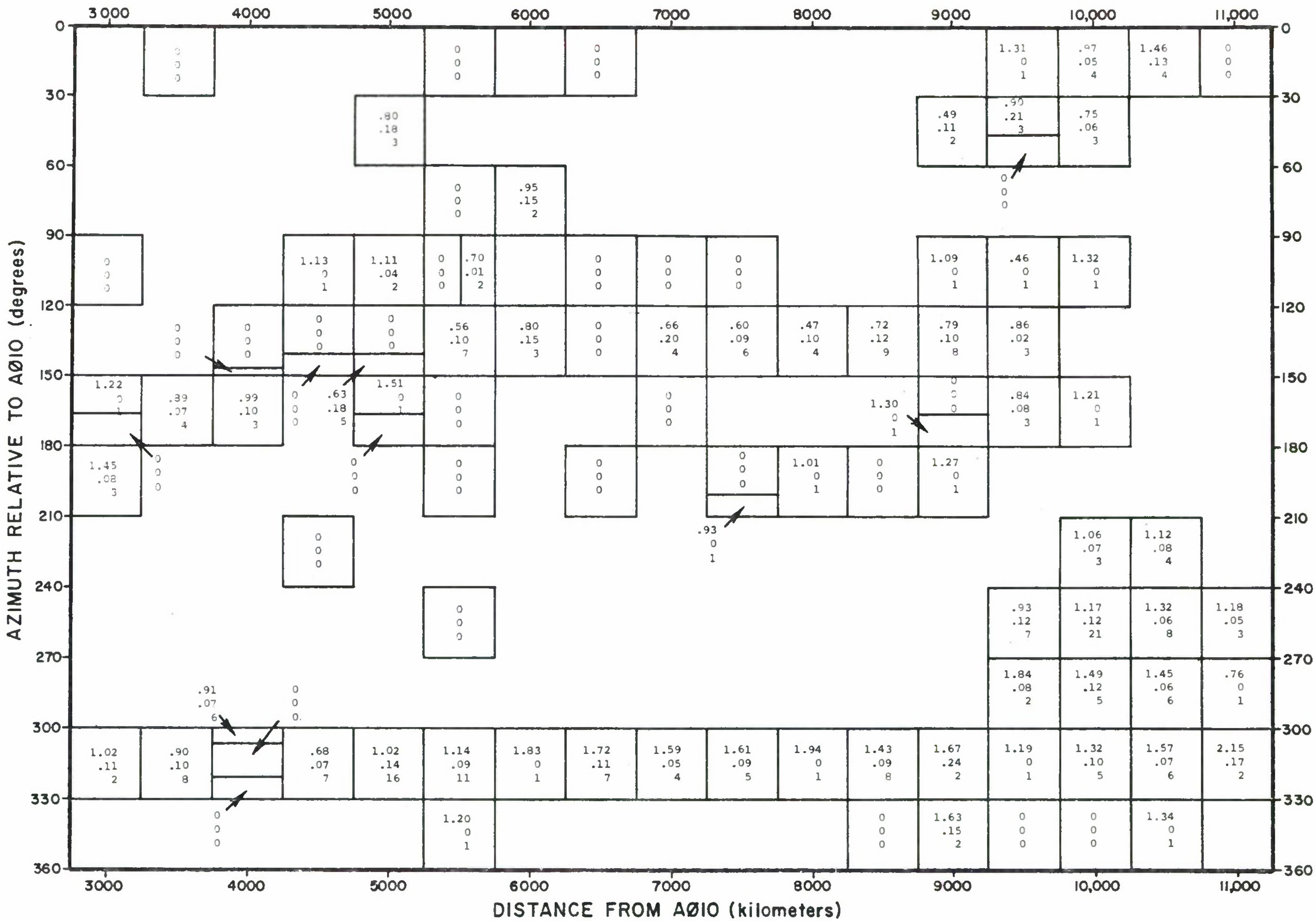


Figure 12. Subarray C3

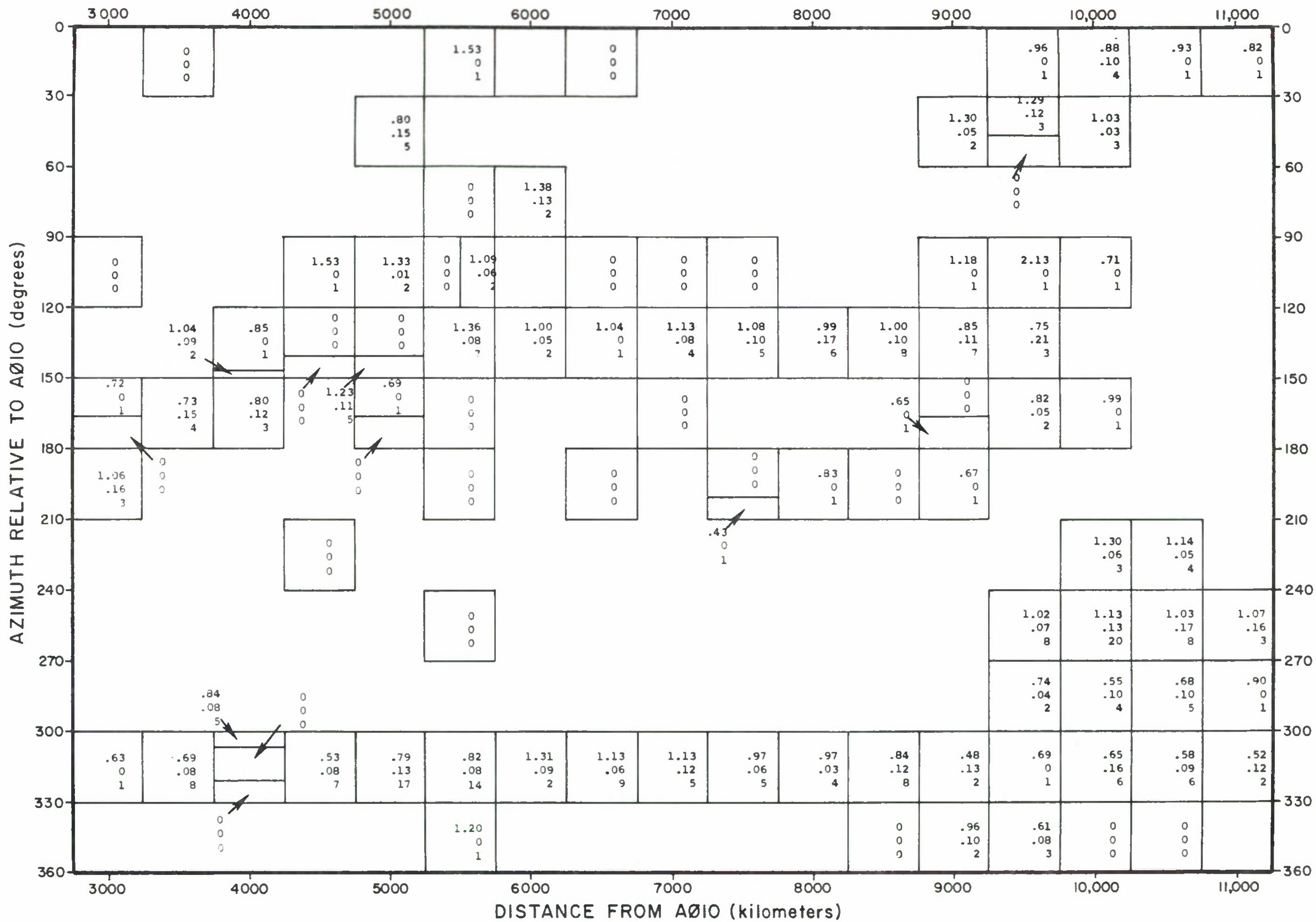


Figure 13. Subarray C4

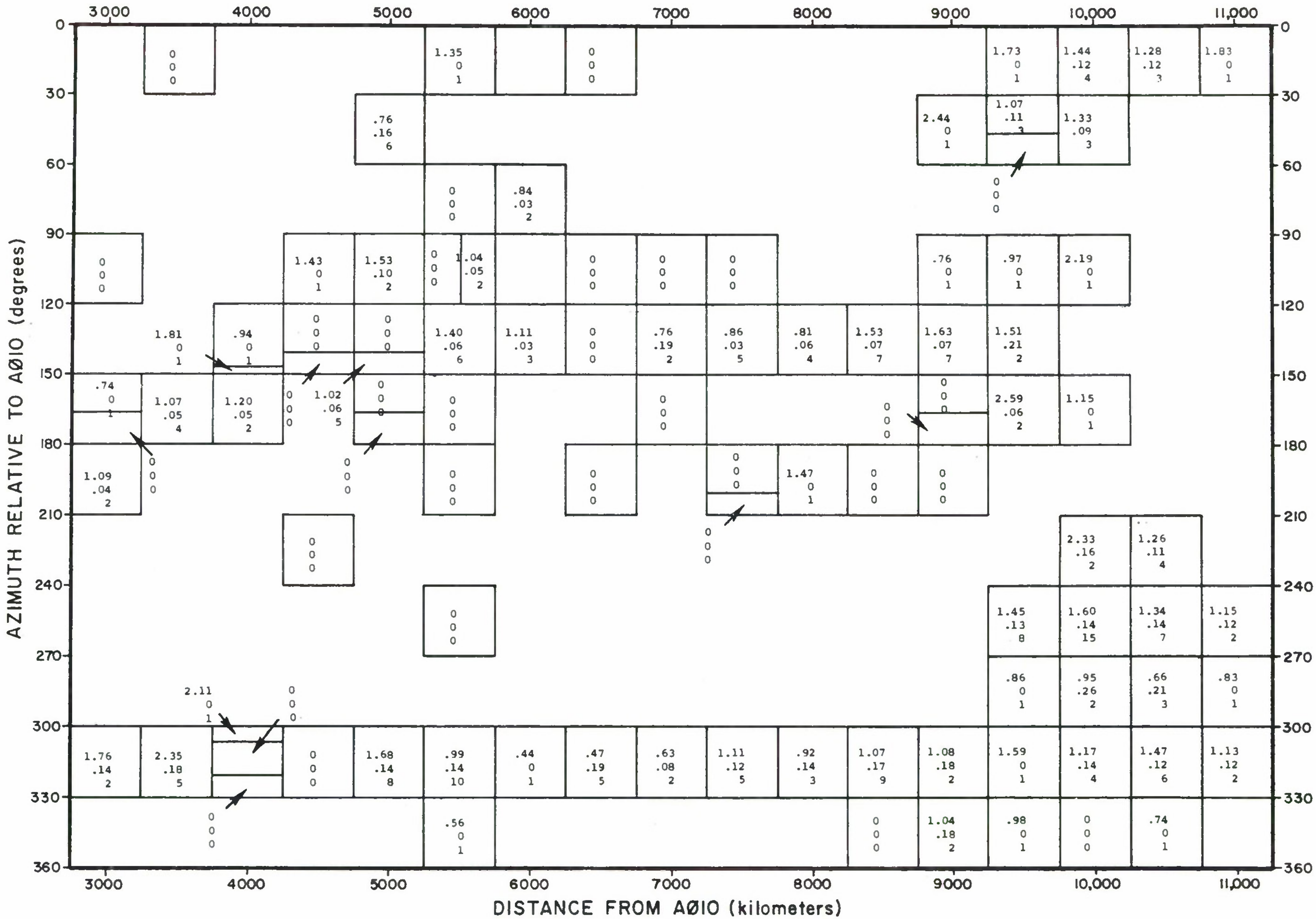


Figure 14. Subarray D1

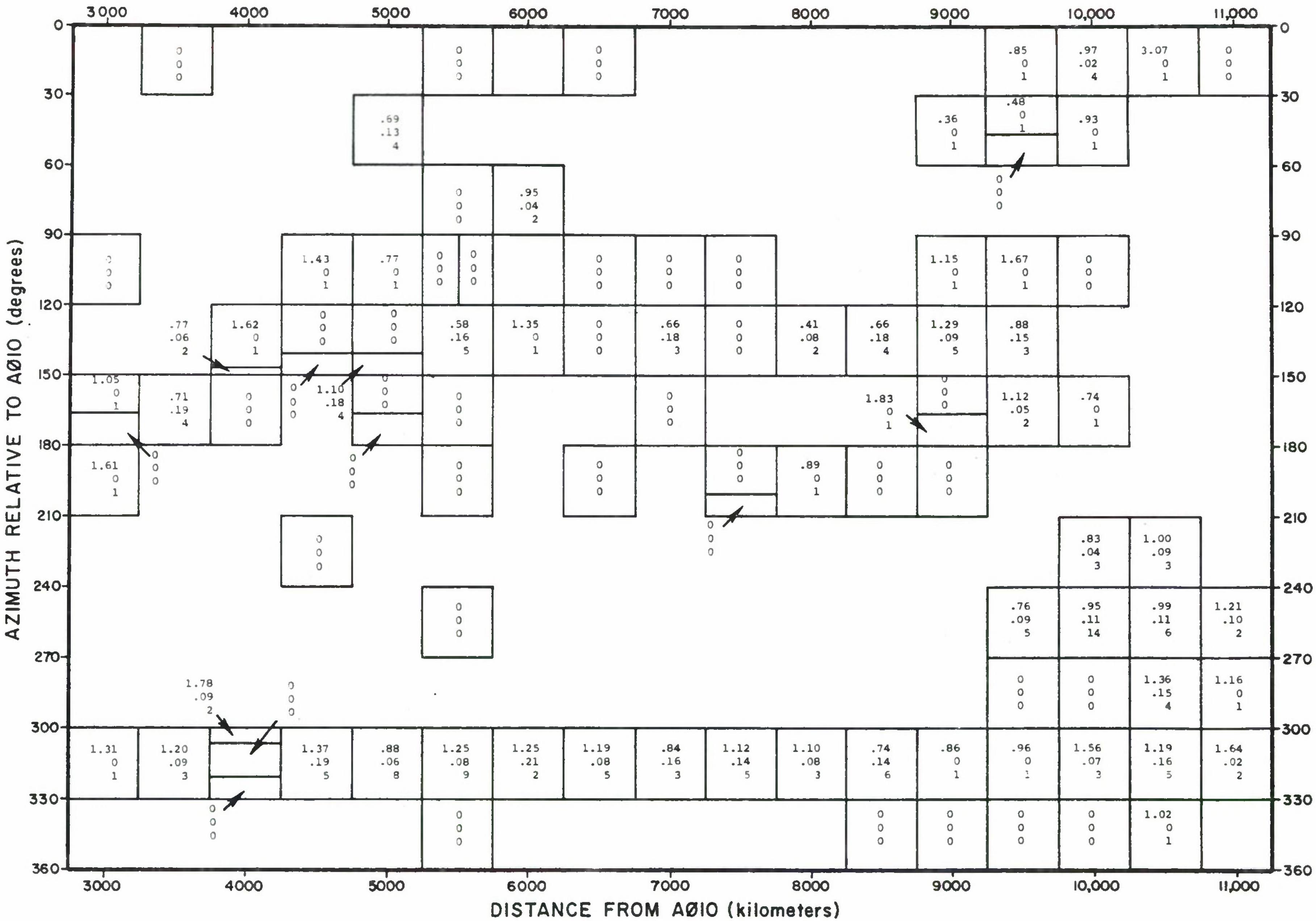


Figure 15. Subarray D2

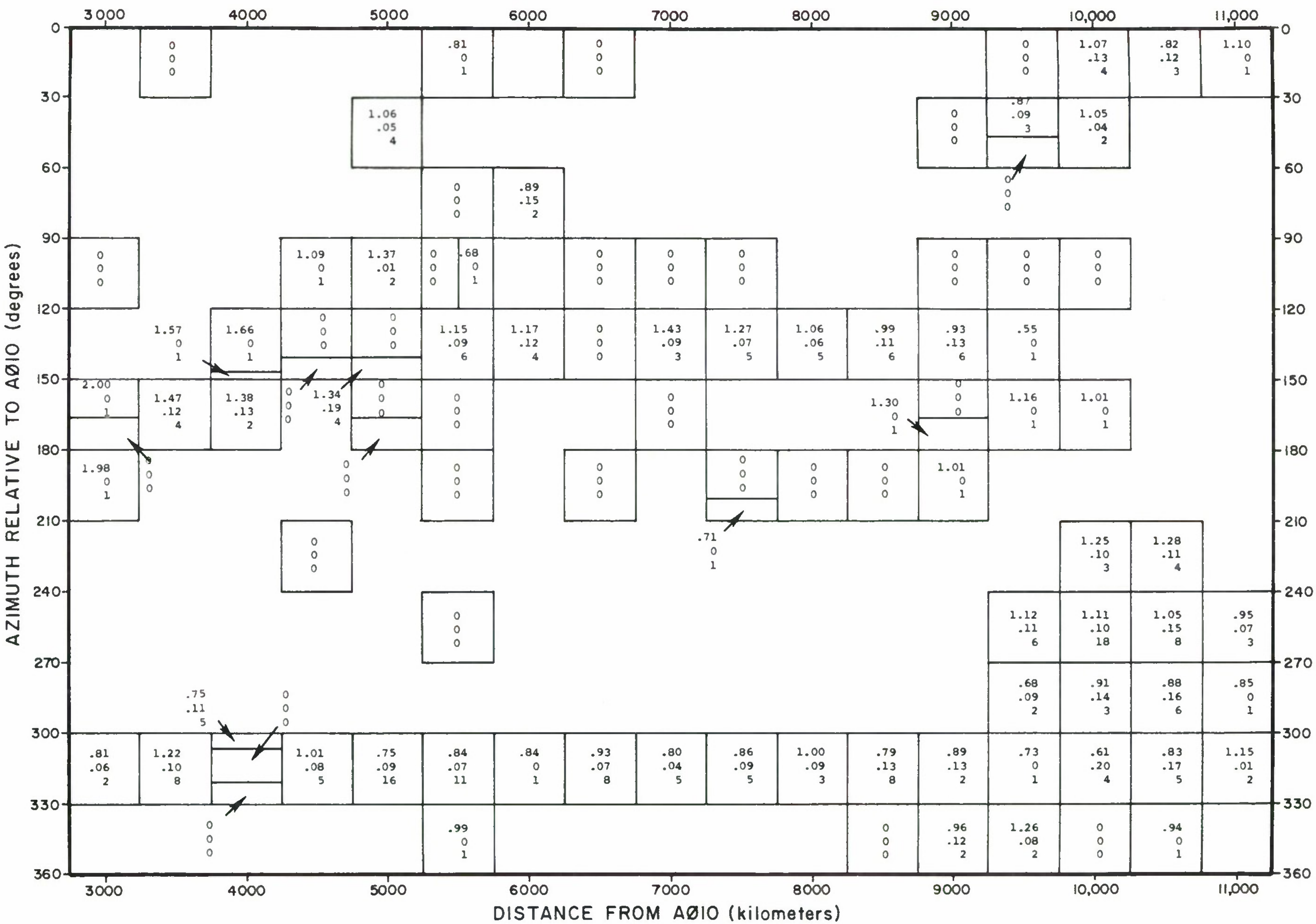


Figure 16. Subarray D3

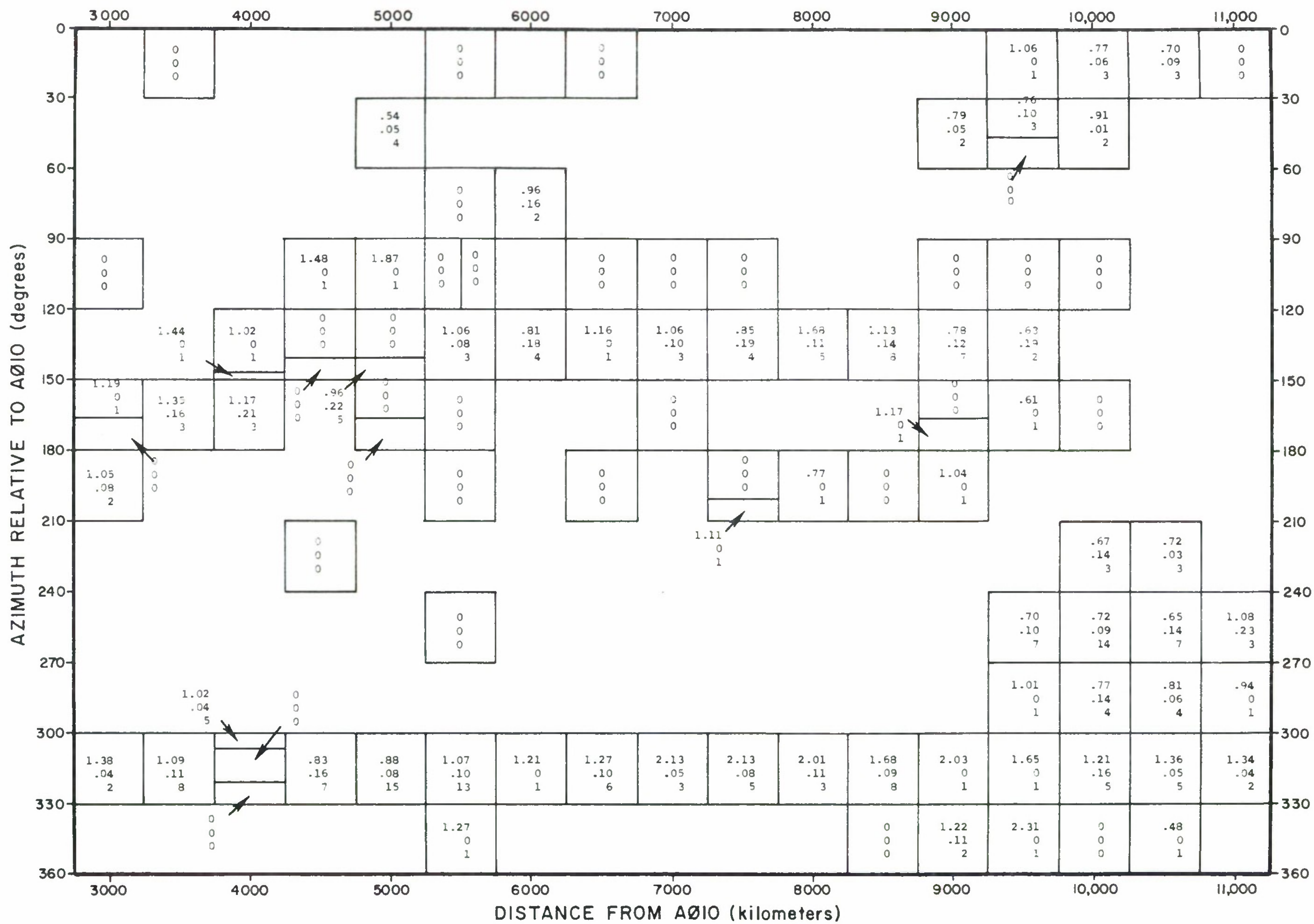


Figure 17. Subarray D4

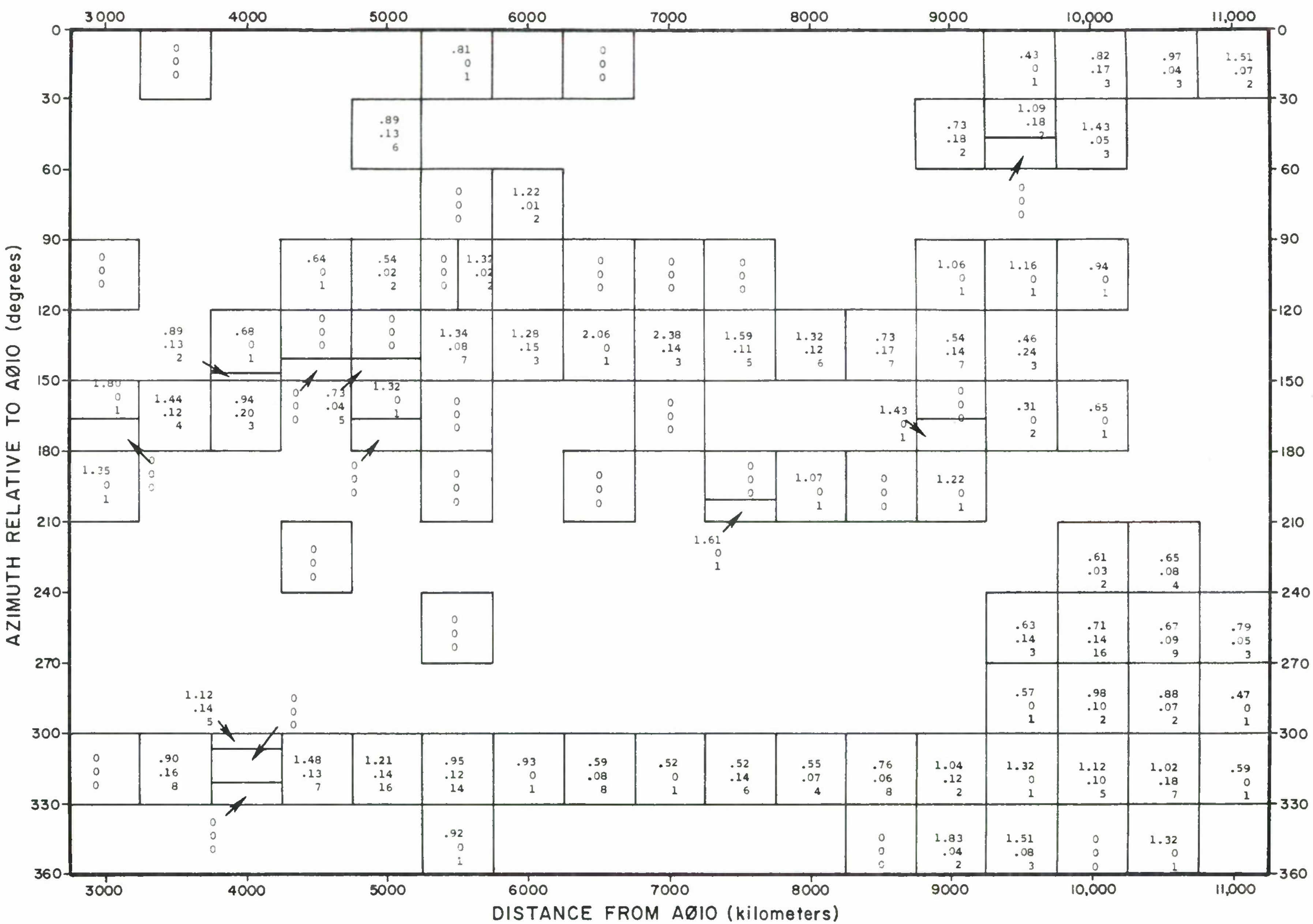


Figure 18. Subarray E1

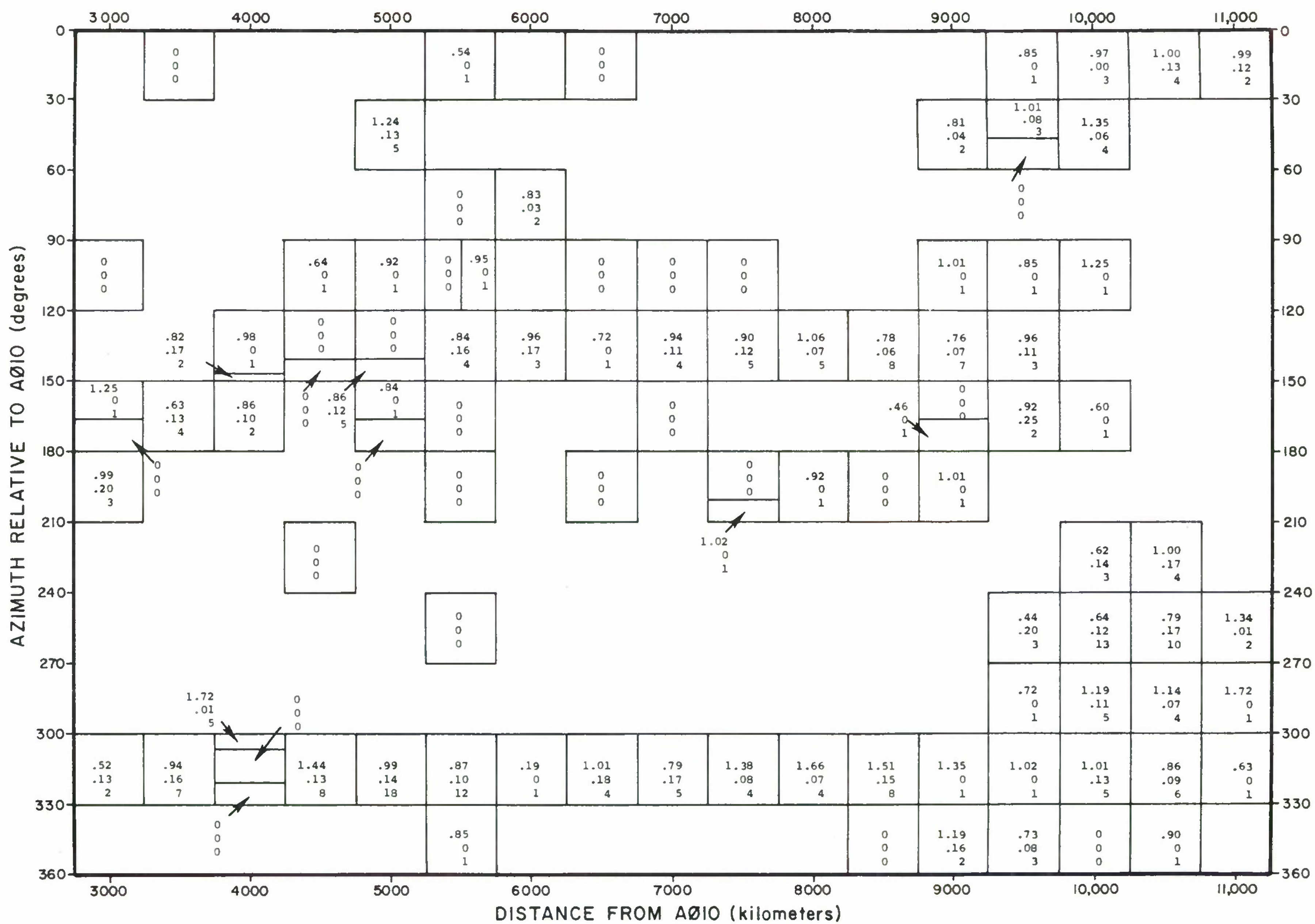


Figure 19. Subarray E2

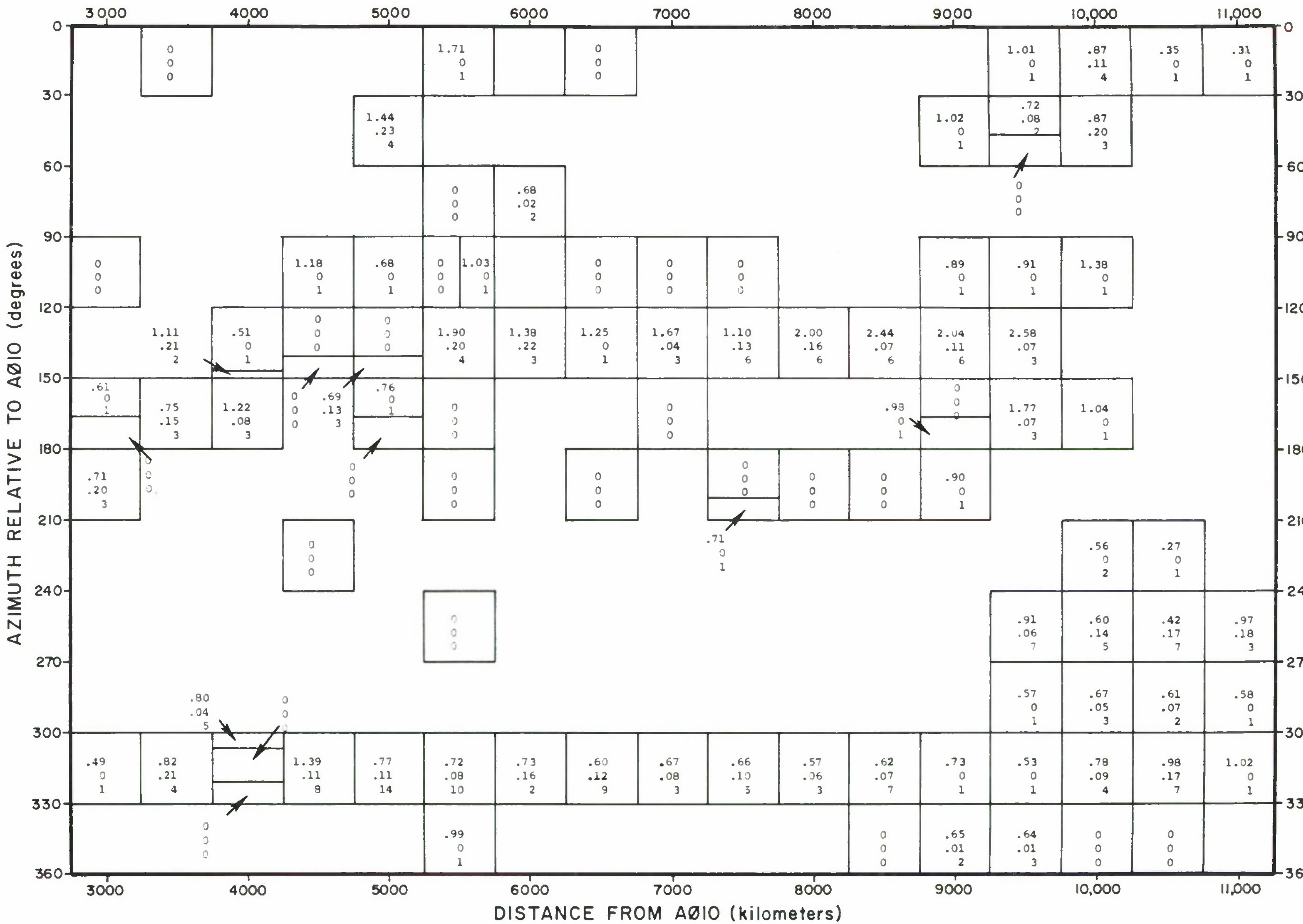


Figure 20. Subarray E3

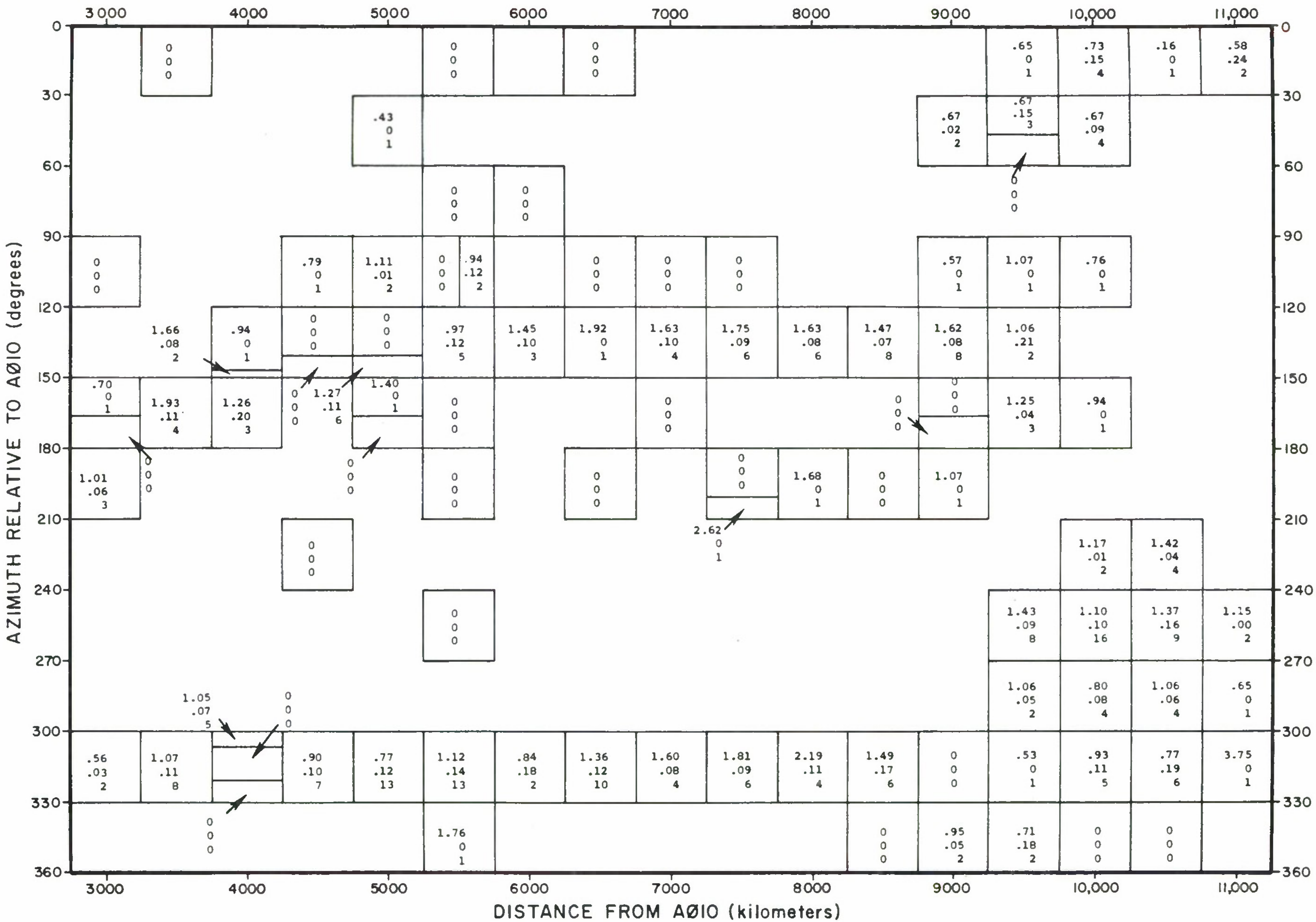


Figure 21. Subarray E4

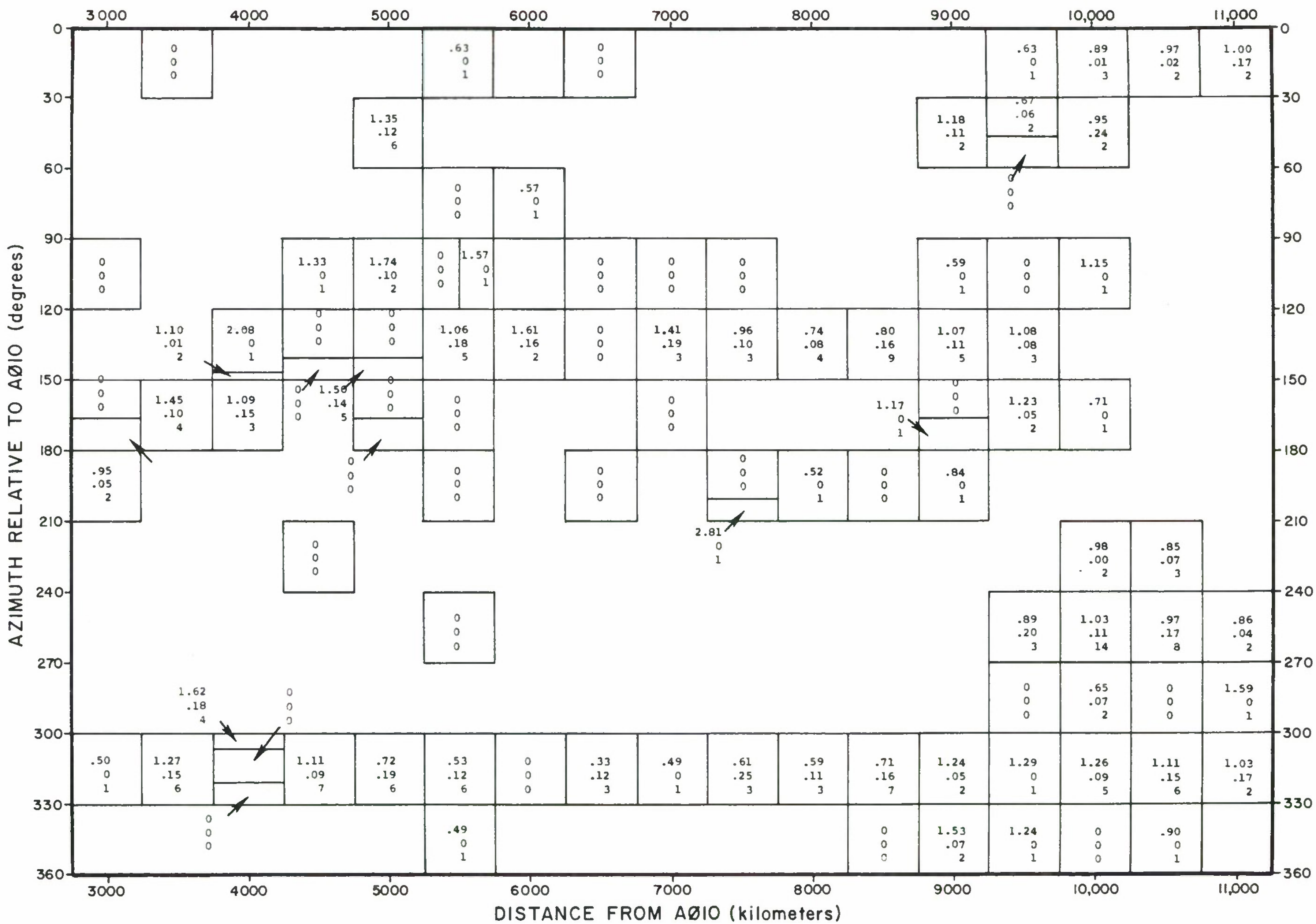


Figure 22. Subarray F1

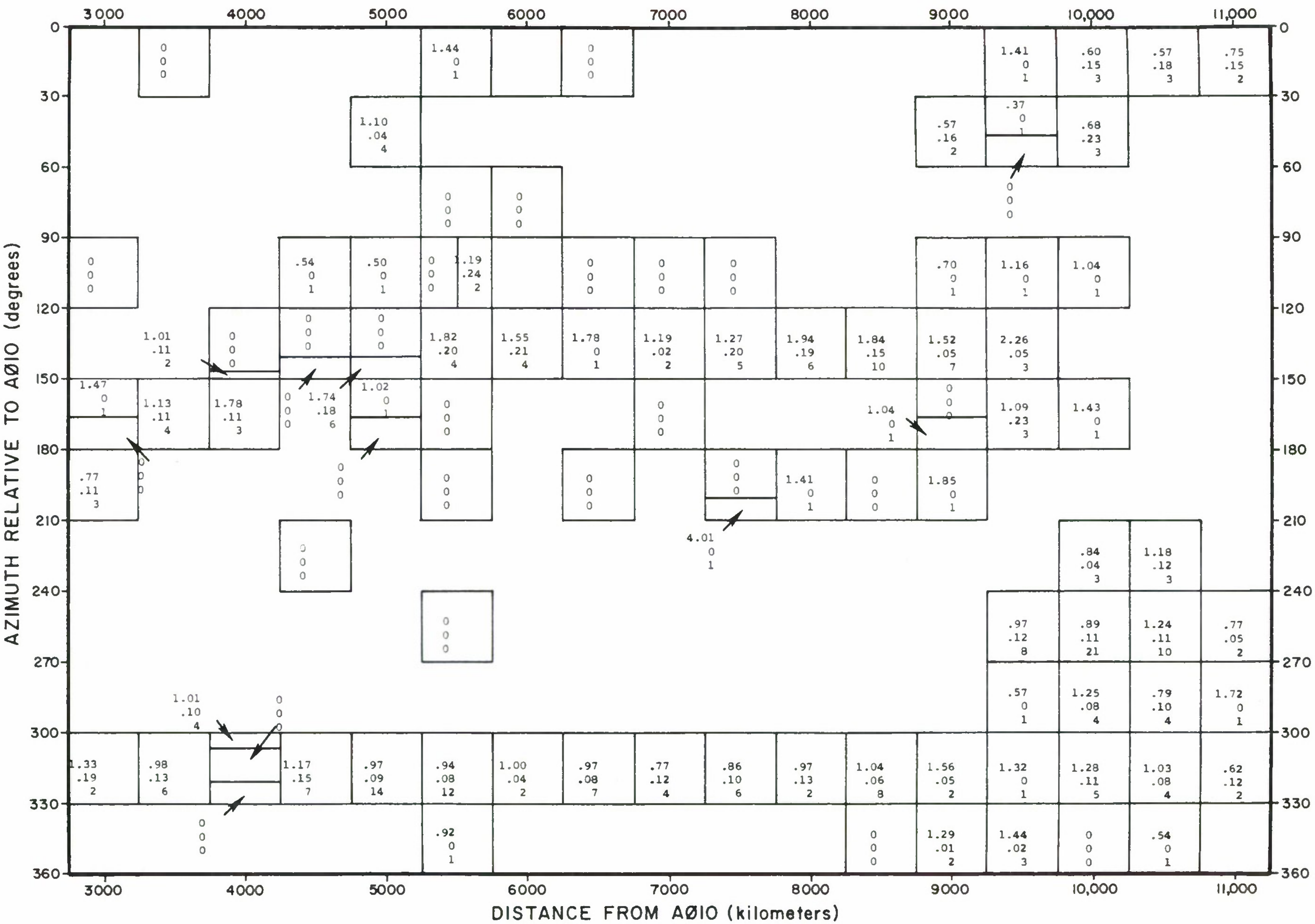


Figure 23. Subarray F2

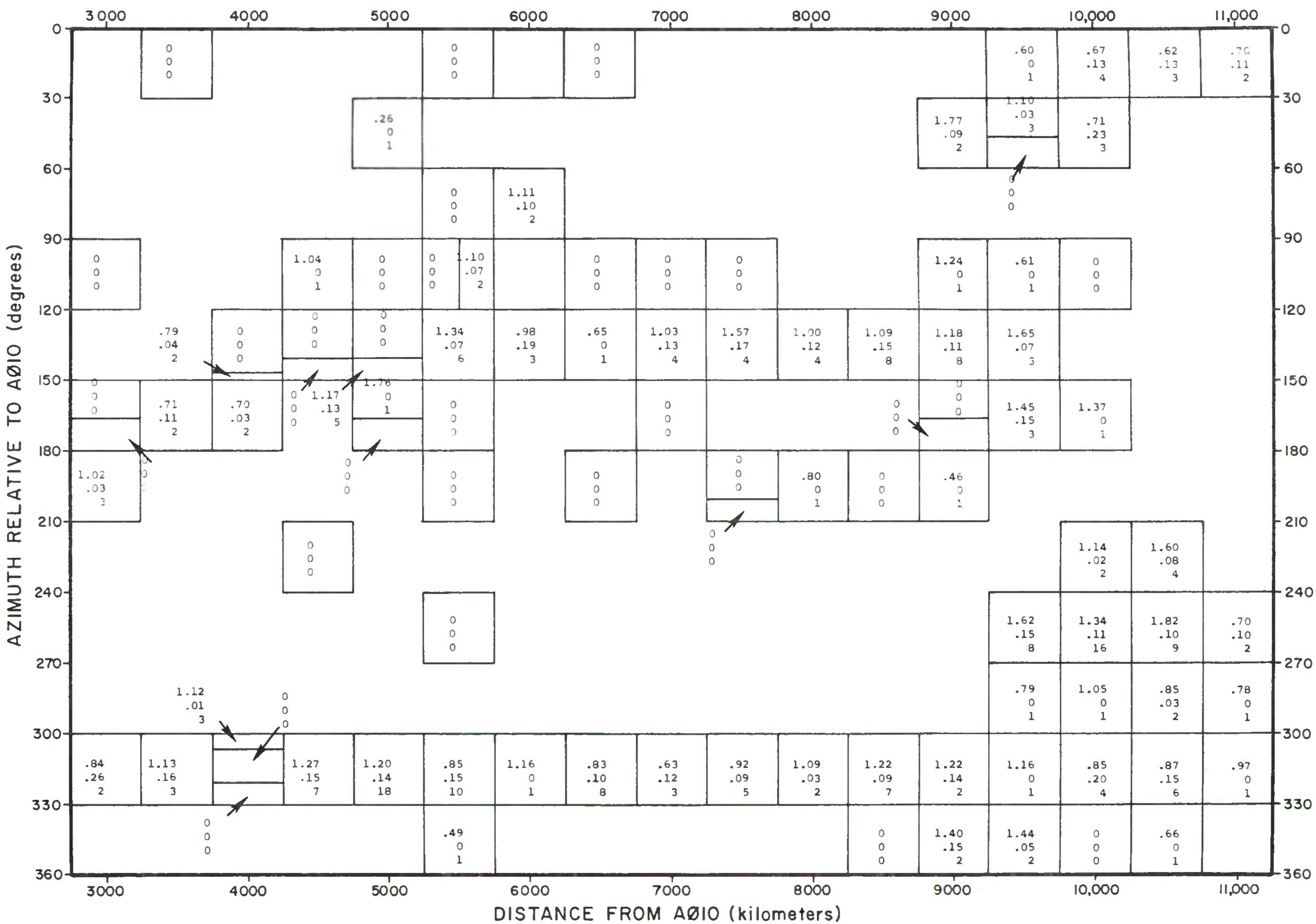


Figure 24. Subarray F3

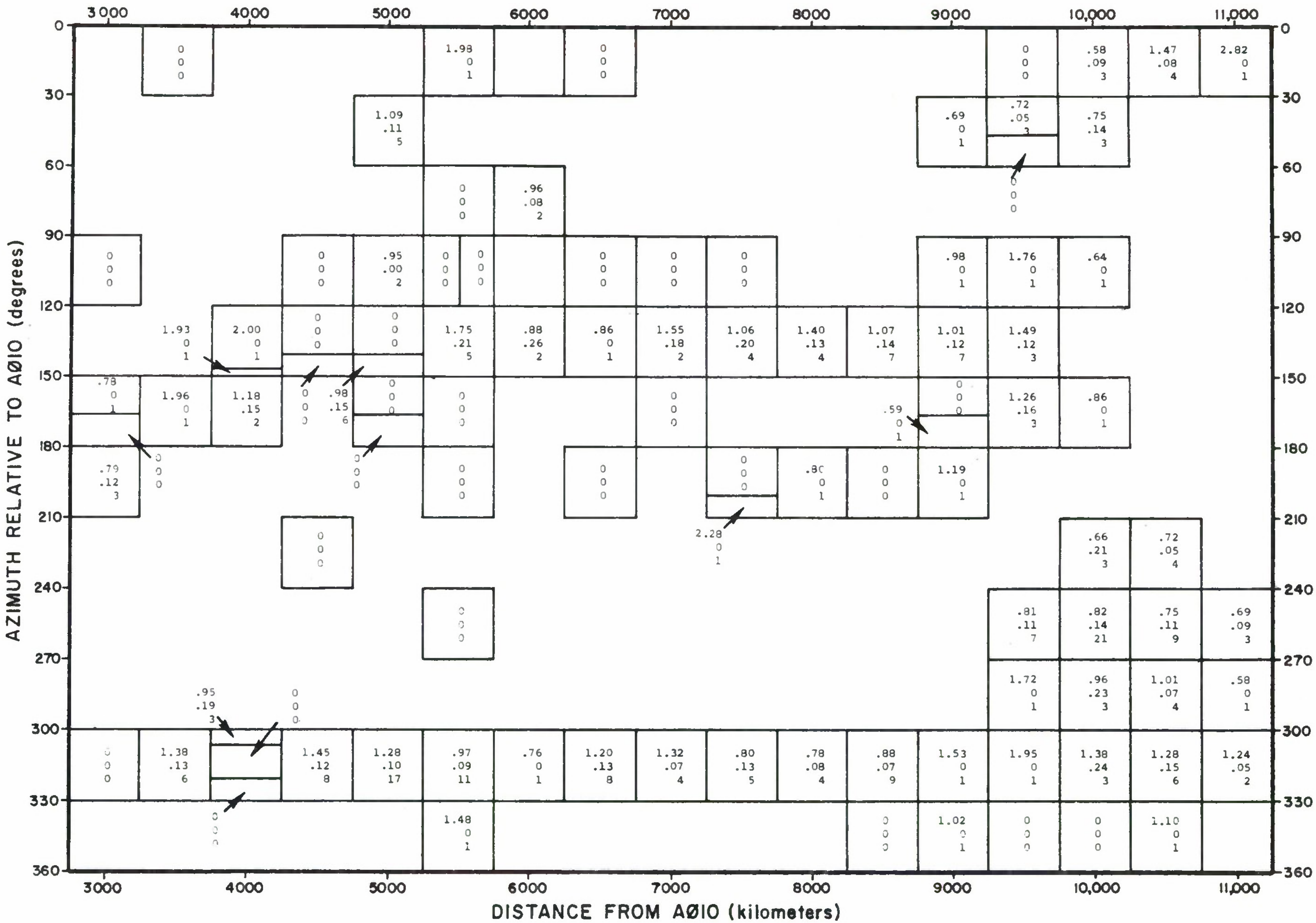


Figure 25. Subarray F4

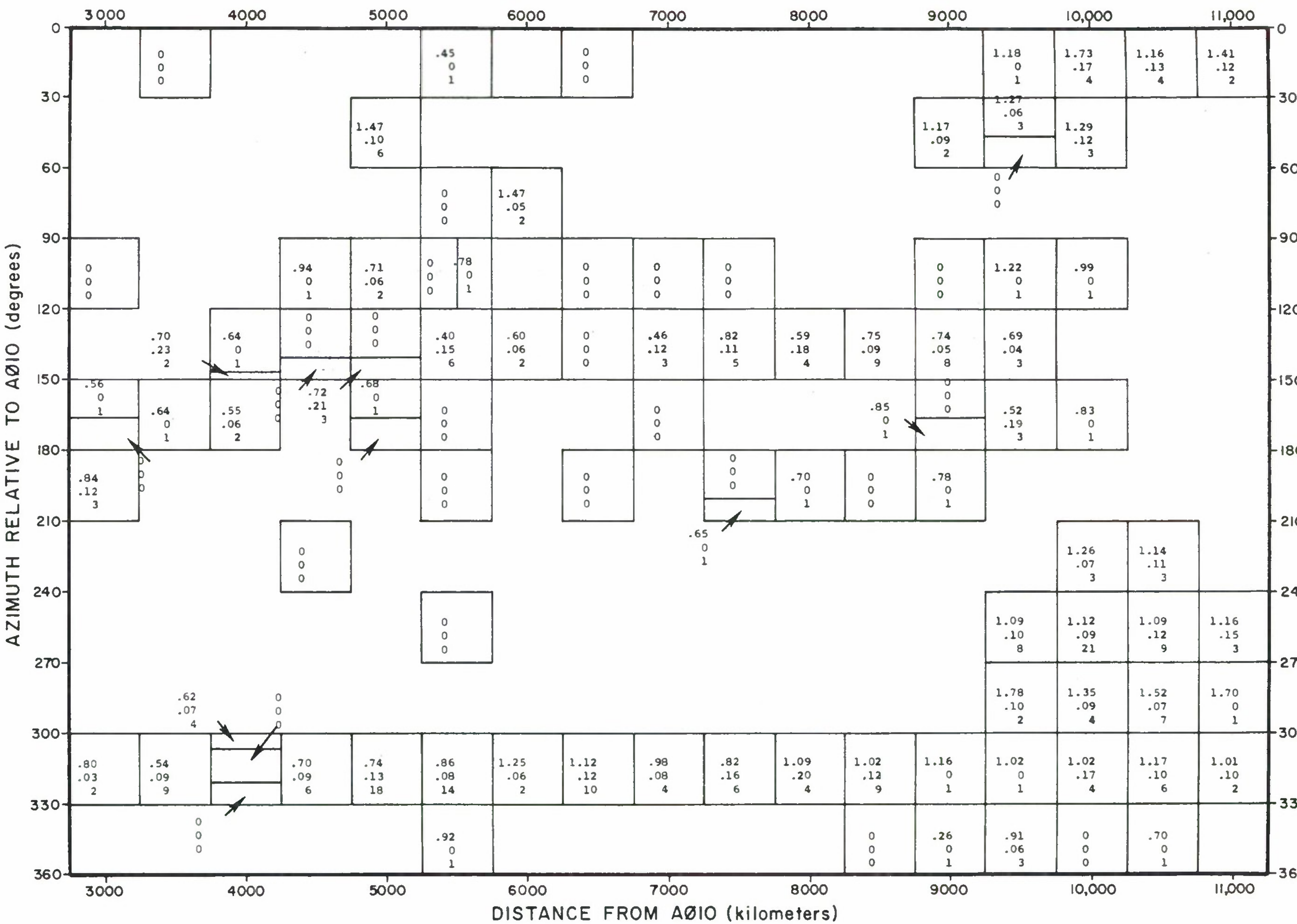


Figure 26. Subarray AO

amplitude for event i and station j, S_i is the radiated signal of event i, g_j is the gain factor of station j, and e_{ij} is an error term which has a log-normal distribution.

The procedure used to detect errors was as follows; The estimates of the variances, S^2, computed for each geographic cell and station were plotted on a histogram as a function of the number of events, N, in that cell. By pooling these variances a very good estimate, $\overline{S^2}$, of the variance of the error population, σ^2, was found. Confidence intervals for the S^2, were then computed and all S^2 which fell outside of the upper 95% confidence limit were questioned. The amplitude measurements involved in computing these outlier-estimates were re-examined for blunders. (Readings which did not clearly include blunders were not changed, so this re-examination of the data should not bias the final results.) The percentage of reading blunders so detected was less than 1% of the total readings taken. With these errors eliminated, the entire process was repeated with the results shown by Figure 27. On this second pass the total number of outliers above the upper confidence limit is 1.1% of the total number of estimates.

4. CONCLUSIONS

It is clear from the results of this study that certain stations at the Large Aperture Seismic Array show a preference "on the average" for events from particular regions. Due to the high variability of the data, however, one might hypothesize that the averaging yields only the low frequency components of an anomaly versus distance-azimuth function which contains, in addition, a considerable amount of high frequency components. The amount of available data is not adequate to provide an answer to this hypothesis. It is interesting to note, however,

that the average anomalies for the eight Fiji events, used in Appendix A to establish the distribution of the errors, have the same distribution function as the errors; see Figures A3 and A4.

The average anomalies are large in many cases, with factors of 3 to 1 between stations being common. As such they must play a part in studies involving the estimation of source radiation patterns. The variability of the data might also put limits on the degree to which one can hope to estimate these radiation patterns using any seismic net: a trade-off between resolution and accuracy likely exists.

The signal model which was derived for error detection served well in that function, however, the model is also interesting in its own right. The physical significance of the multiplicative error factor was not to be part of this study, and for this reason no effort was made to explain it. It is possible that the effect could have some bearing upon the placement of new arrays.

The data, as presented, is adequate to describe the average amplitude anomalies in the more seismically active regions.

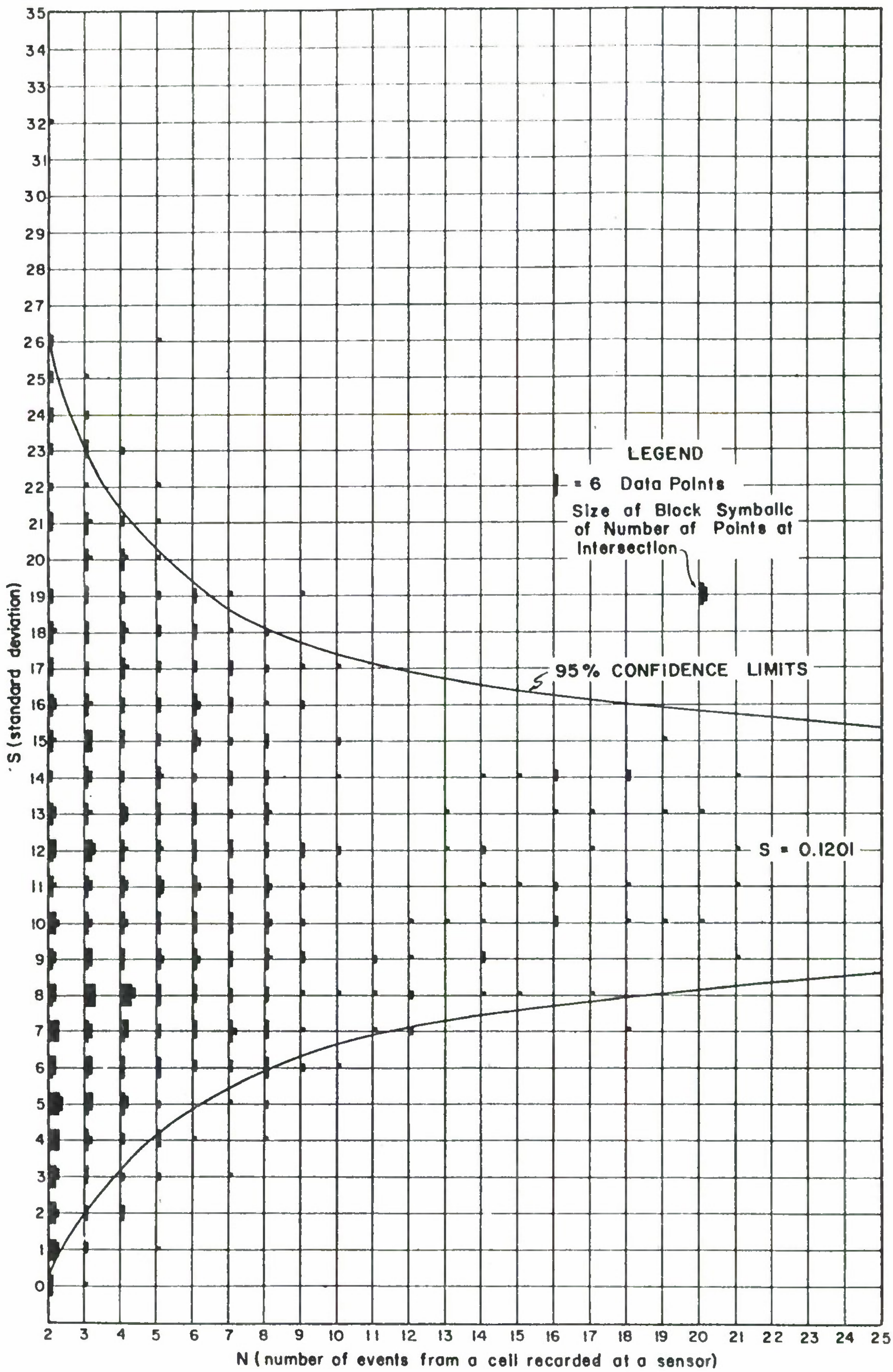


Figure 27. Distribution of Standard Deviation Estimates Computed from N Event

APPENDIX A

A.1 INTRODUCTION

The signal levels recorded at the stations, aside from statistical variations, will be

$$L_{ij} = S_i g_j \tag{A-1}$$

where S_i is the signal radiated by the ith event and g_j is a gain associated with the jth station. The set of ratios of these levels for a single event are termed "amplitude anomalies". We define an individual anomaly for stations ℓ and m as

$$A_{\ell mi} = L_{\ell i}/L_{mi} \tag{A-2}$$

note that

$$A_{m\ell i} = (A_{\ell mi})^{-1} \tag{A-3}$$

and denote the set of these as

$$\bar{A}_i = \left\{A_{\ell mi}\right\}_{\ell,m=1}^{21} \tag{A-4}$$

All elements in $\bar{A}_i$ are equally important but only 20 of the 441 are independent. Any 20 which contain each station index at least once are sufficient to construct the entire set.

In analyzing the recorded signals, it was found that $\bar{A}_i$ was highly variable. To reduce this variability, averages were taken over events from the same region. This pooling of

events is possible under the assumption that amplitude anomalies are a slowly varying function of distance and azimuth.* Thus, if the region is sufficiently small, this is equivalent to assuming the anomalies are constant for each region.

Several approaches were taken to this pooling problem. Each of these was equivalent in the sense that they all produce the same final results. A summary of these will be presented in the remainder of this section.

A.2.1 Method 1

From Equation (A-3) we note that the apparent size of an anomaly depends upon the reference station. To eliminate this effect, a logarithmic transformation was made.

Since, on a logarithmic scale, the reference station which is chosen serves only to translate all anomalies equally, we can dispense with a reference station momentarily and concentrate instead on a set of translating factors.

First, consider the problem of fitting the observed amplitudes for a single event to a selected level S. We seek a multiplier or normalizing factor, G_i, to minimize the total deviation from S,

$$\epsilon_i = \sum_{\substack{j \\ \text{stations}}} (\log S - \log G_i L_{ij})^2 \tag{A-5}$$

*This assumption is open to question. It is clear from the results of this study, however, that certain stations do show a preference "on the average" for events from particular regions. From the data, though, one might hypothesize that the averages yield only the slowly varying components of a distance-azimuth function which contains a considerable amount of high frequency components. The amount of available data is not adequate to answer this question.

and find that

$$G_i = S / \left(\prod_{j=1}^{J} L_{ij} \right)^{1/J} \tag{A-6}$$

where J is the total number of stations.

Second, consider minimizing the total variation between events. We define this total variation as

$$V = \sum_{\substack{j \\ \text{station}}} \sum_{\substack{i,k \\ \text{events}}} (\log G_i L_{ij} - \log G_k L_{kj})^2 \tag{A-7}$$

where the G are multiplicative factors as before.

This minimum will be found among the solutions to the equations

$$\frac{\partial V}{\partial G_n} = 0, \qquad n = 1, 2, \ldots \tag{A-8}$$

or

$$\sum_{j,k} \frac{2}{G_n} (\log G_n L_{nj} - \log G_k L_{kj}) = 0 \tag{A-9}$$

which reduces to

$$I \log G_n^J = \sum_{j,k} \log \frac{G_k L_{kj}}{L_{nj}} \tag{A-10}$$

where I and J are the total number of events and stations respectively.

By setting

$$\sum_{j,k} \log G_k L_{kj} = IJ \log S, \tag{A-11}$$

a constant, we obtain

$$G_i = S / \left(\prod_{j=1}^{J} L_{ij} \right)^{1/J} \tag{A-12}$$

as before.

The constant S can be chosen arbitrarily. The weights G_i are independent and the normalizing process is equivalent to fitting, in a least-square sense, each set of measurements, L_{ij}, to a reference level Log S. This permits addition or omission of events from a collection without disturbing the normalization factors on the remaining data. In this way we obtain a set of normalizing factors which can be used on an event by event basis.

The normalized amplitudes can be plotted as ordinates on semi-log graph paper with stations as abscissa on the linear axis. The resultant plots will be adjusted in a least-squares sense to minimize the total variation.

To use these data for computing anomalies we first define the average normalized amplitude at each station as

$$\log g_j = \langle \log G_i L_{ij} \rangle = \frac{1}{I} \sum_{\substack{i=1 \\ \text{events}}}^{I} \log G_i L_{ij} \tag{A-13}$$

where the G_i are previously determined normalizing factors. Then the average anomaly is given as

$$\langle A_{m\ell i} \rangle = \log^{-1} \left[\langle \log G_i L_{im} \rangle - \langle \log G_i L_{i\ell} \rangle \right]$$

$$= \prod_{i=1}^{I} \frac{L_{im}}{L_{i\ell}}^{1/I} \tag{A-14}$$

which is the geometric mean of the individual anomaly estimates. This reasonable result, along with the desirable features of the logarithmic transformation are reason enough for using this method.

A.2.2 Method 2

Up to this point in the analysis it was not necessary to incorporate an error model. To lend further justification to the above method, however, it was felt desirable to do this. We therefore assumed an error model of the form

$$L_{ij} = S_i \, g_j \, e_{ij} + \varepsilon_{ij} \tag{A-15}$$

where ε_{ij} is due to the additive factors of noise and reading errors and e_{ij} accounts for variation in system gain due to equipment changes, effects of wave-shapes, etc.

The steps taken will be to assume and then justify two hypotheses which were put forth after looking at a large amount of data. These assumptions are that the additive noise ε_{ij} is negligible for large events and that e_{ij} has a log normal distribution.

By neglecting the additive error, one may linearize the model to

$$\log L_{ij} = \log S_i + \log g_j + \log e_{ij} \tag{A-16}$$

and by minimizing the sum of squares

$$E = \sum_{i,j} (\log e_{ij})^2 = \sum_{i,j} \left(\log \frac{L_{ij}}{S_i g_j}\right)^2 \tag{A-17}$$

estimate the values of S_i and g_j (albeit not independently).

These critical values of gain and signal level are in the solutions to the equations

$$\frac{\partial E}{\partial s_n} = 0 \text{ and } \frac{\partial E}{\partial g_m} = 0 \qquad \begin{array}{l} n = 1,2,\ldots,I, \\ m = 1,2,\ldots,J \end{array} \tag{A-18}$$

or

$$\sum_j \text{Log } (L_{nj}/s_n\ g_j) = 0 \tag{A-19.1}$$

and

$$\sum_i \text{Log } (L_{im}/s_i\ g_m) = 0 \tag{A-19.2}$$

which can be rewritten as

$$s_n = \left(\prod_{j=1}^{J} L_{nj}/g_j \right)^{1/J} \tag{A-20.1}$$

and

$$g_m = \left(\prod_{i=1}^{I} L_{im}/s_i \right)^{1/I} \tag{A-20.2}$$

Then by adding one constraint, namely that

$$\prod_{j=1}^{J} g_j = s^J \tag{A-21}$$

we have

$$g_m = \frac{\left(s \prod_{i=1}^{I} L_{im}\right)^{1/I}}{\left(\prod_{ij=1}^{IJ} L_{ij} \right)^{1/IJ}} \tag{A-22}$$

which is equivalent to Equation (A-12) when I=1 and $g_m = G_i\ L_{im}$.

The anomalies are, as before, ratios of the estimates of the gain factors,

$$< A_{m\ell j} > = g_m / g_\ell \qquad \text{(A-23)}$$

$$= \prod_{i=1}^{I} (L_{im} / L_{i\ell})^{1/I} \qquad \text{(A-24, A-14)}$$

A.3 Distribution of Errors

To establish the distribution function for e_{ij}, eight events from the Fiji Islands were normalized using (A-6) with S = 1 as shown in Figure A-1. The average gain of each station was computed using (A-22), and the deviations from these averages were plotted as shown in Figure A-2. This data was then broken into class intervals and plotted on a logarithmic probability graph, Figure A-3.

The fit to a log-normal distribution function is sufficiently good to justify the assumptions that the additive noise is negligible for our purposes provided we use large events. Also, since the error term in the linearized model is distributed normally, classical least squares methods with the usual statistical qualifications on all estimates can be applied directly.

Another way of presenting this data is shown in Figure A-4. There the observed amplitudes for these events are plotted against the model values, namely observed log L_{ij} versus log S_i + log g_i, where S_i and g_i are estimated using Equations (A-20) and (A-21).

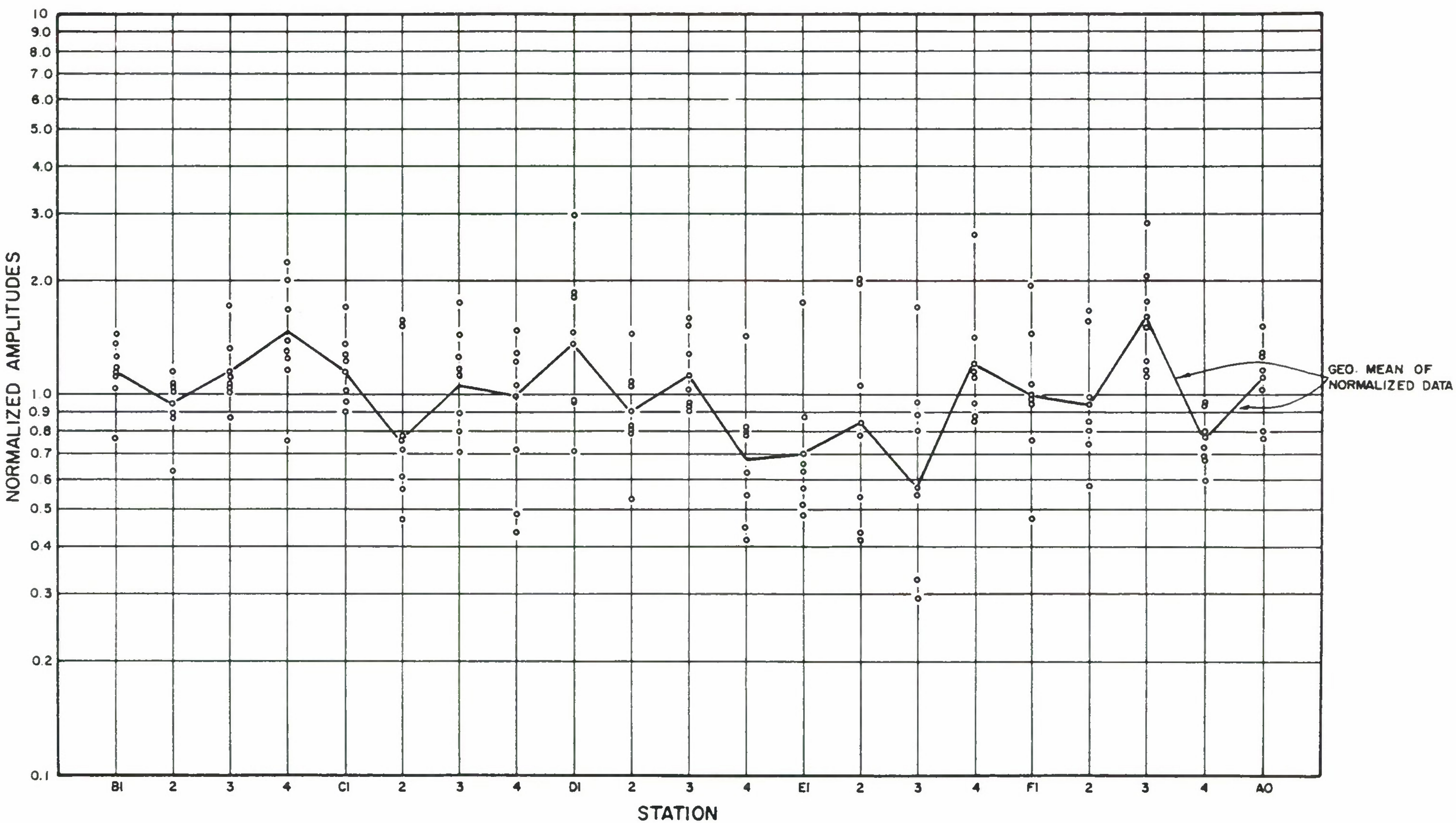


Figure A-1. Eight Fiji Island Events - Normalized and Showing the Means for Each Station

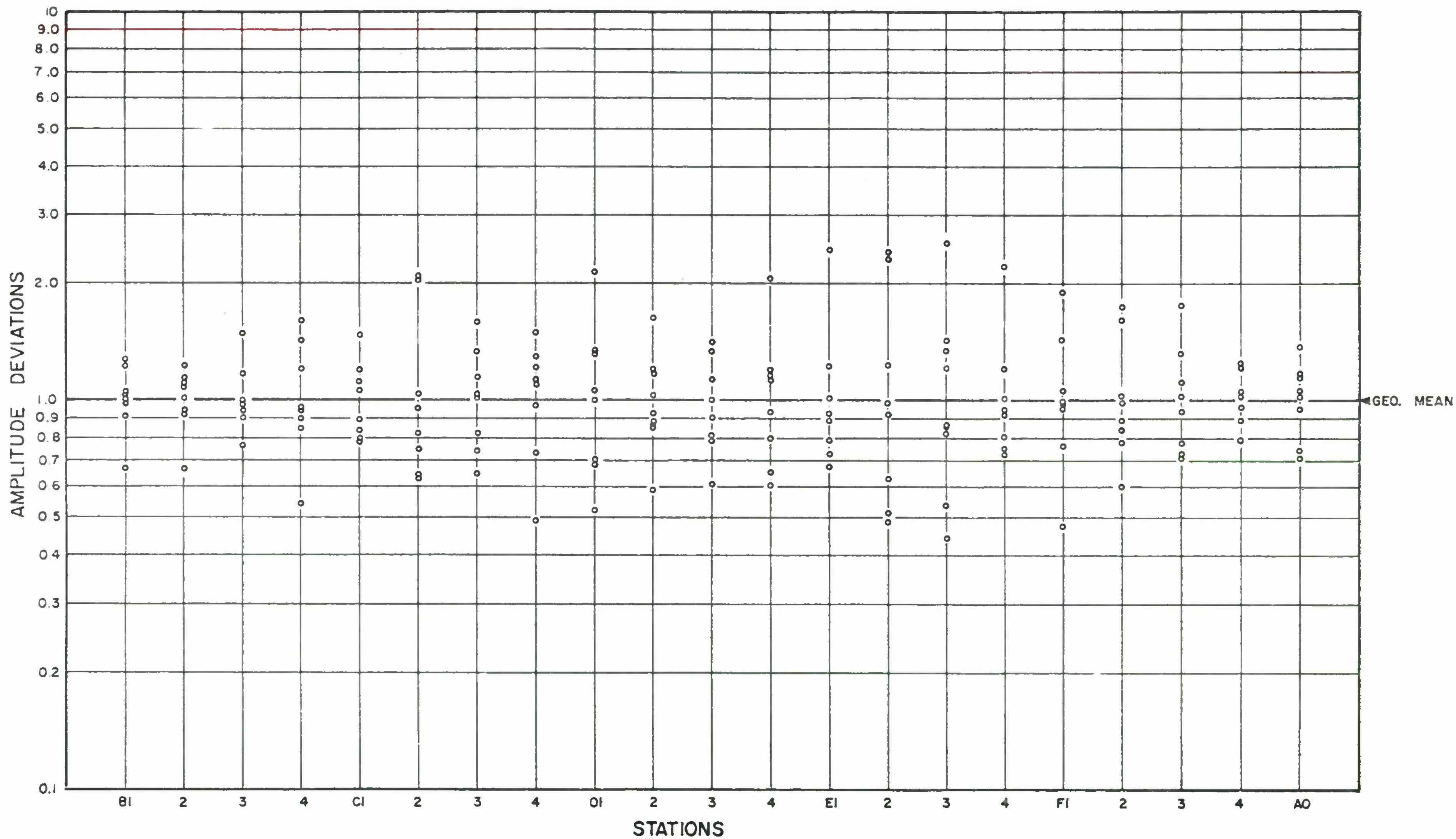


Figure A-2. Eight Fiji Island Events Showing Deviations about the Mean Amplitudes

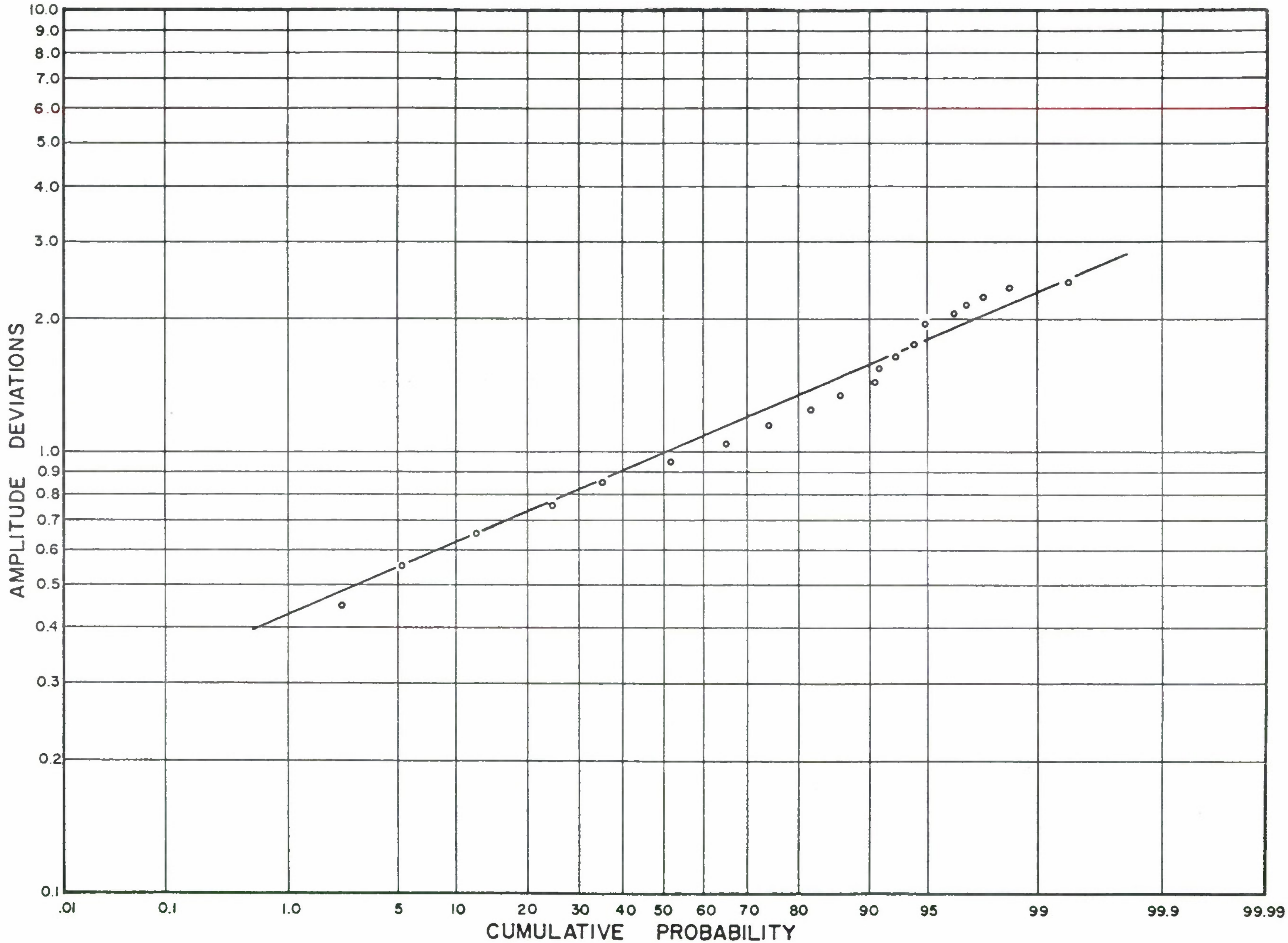


Figure A-3 Distributions of the Amplitude Deviations of Eight Fiji Island Events

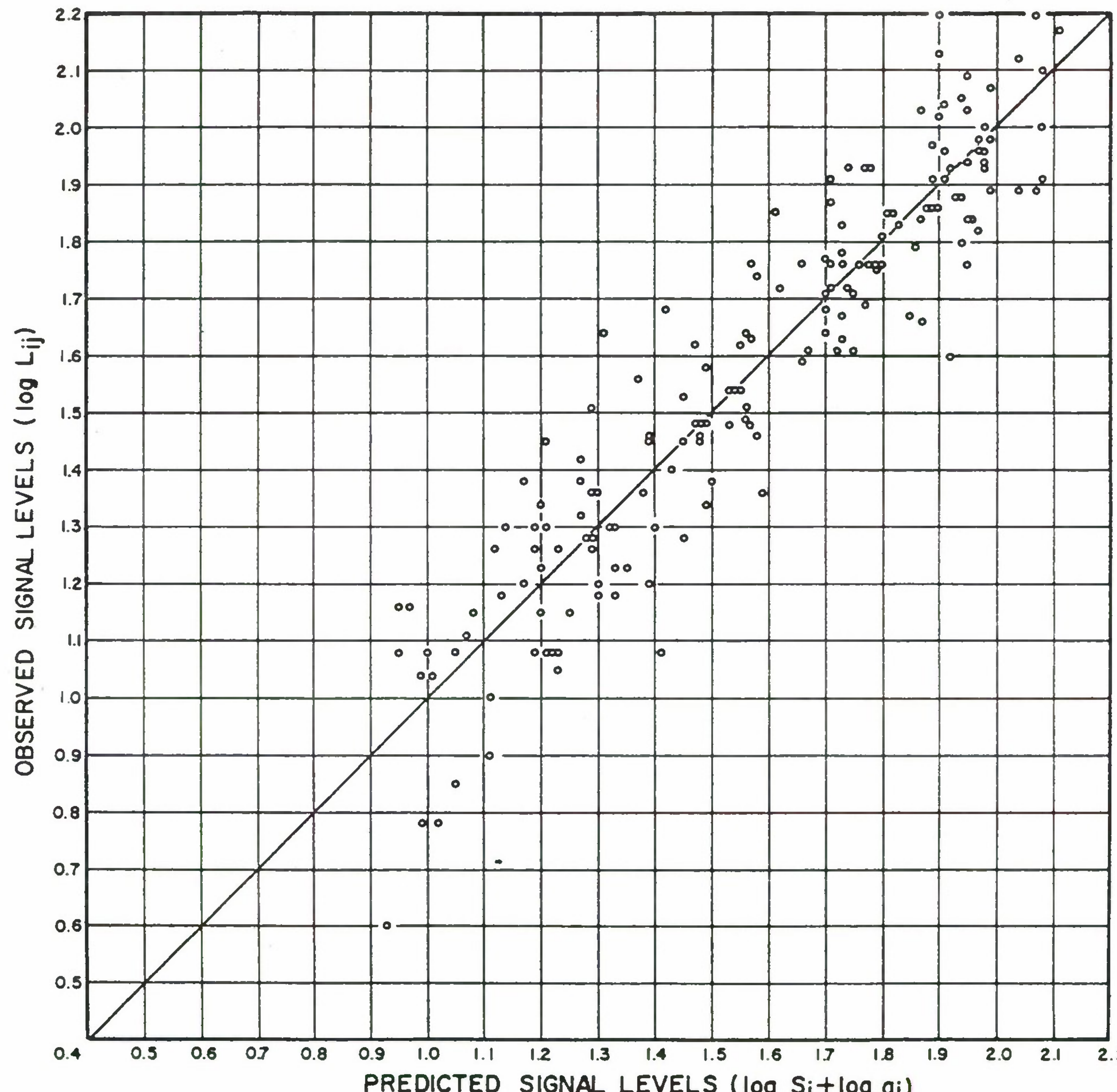


Figure A-4. Observed versus Predicted Signal Levels - 8 Fiji Island Events. Using a Product Error Model with Zero Additive Noise Assumed.

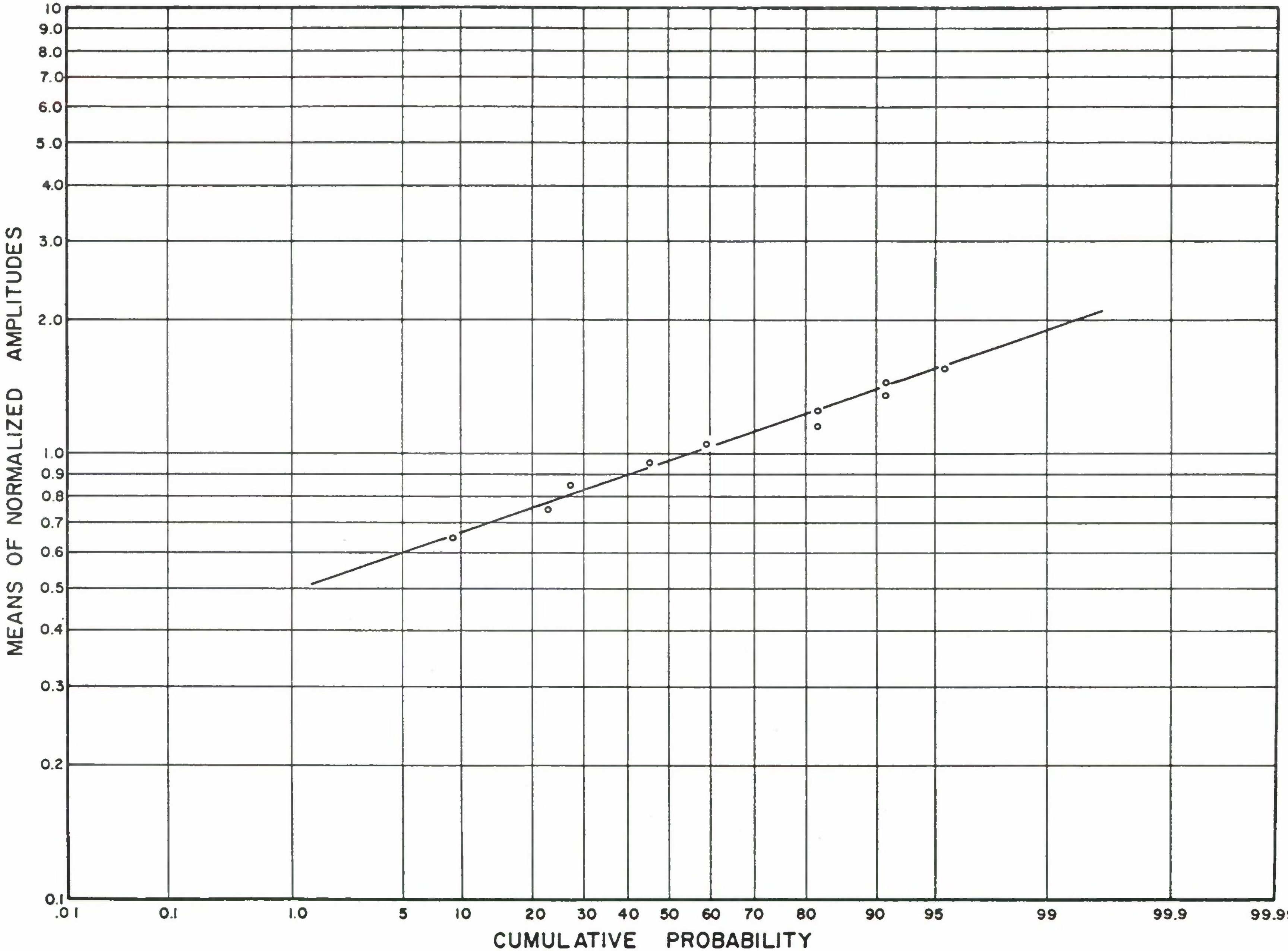


Figure A-5. Distribution of Means of Normalized Amplitudes for Eight Fiji Island Events

APPENDIX B

SEISMIC DATA LABORATORY
ALEXANDRIA, VIRGINIA

DIGITAL COMPUTING SECTION

A. IDENTIFICATION

Title: ANOMALY

COOP Identification: Z108

Category: General

Programmer: Nicholas Fletcher

Date: 16 June 1966

B. PURPOSE

To compute travel-time and amplitude anomalies

C. USAGE

1. Operational Procedure: This is a FORTRAN 63 program. All input is from punched cards and the output is from the printer, and an off-line card image tape.

2. Parameters: Input parameters consist of the latitude and longitude of the location of the subarray centers.

3. Space Required: Not Applicable

4. Temporary Storage Requirements: None

5. Alarms: None

6. Error Codes: None

7. Error Stops: None

8. Input and Output Tape Mounting: There is no input tape. The output tape is on logical Unit 16.

9. Input and Output Formats:

The input card formats are as follows:

Subarray locations deck, must be the first deck of cards read by the program. The first card of this deck must contain the number of subarray location cards. This number is punched in Columns 1 through 5 right justified. The first card is followed by the subarray location cards, with one location per card. The program is limited to a maximum of 51 subarrays. 1 (One) punched in Column 10, prints out J. B. Table and station locations.

Subarray location card format is as follows:

FORMAT (A8, 2 (F5.0, F3.0, F5.1, A1)

COLS.

1-8	Subarray name, left justified
9-13	Subarray latitude degrees
14-16	Subarray latitude minutes
17-21	Subarray latitude seconds (with decimal point punched)
22	N or S for north or south latitude
23-27	Subarray longitude degrees
28-30	Subarray longitude minutes
31-35	Subarray longitude seconds (with decimal point punched)
36	E or W for east or west longitude

The location cards are followed by the first event card ----

Event Card Format is as follows:

Columns 1 through 14 contain the origin time of the event

COLS.

1-2	Month
3-4	Day

COLS.

5-6	Year
7-8	Hour
9-10	Minute
11-14	Second to the nearest tenth of a second
15-18	Latitude of the event in degrees to the nearest tenth
19	N or S for north or south
20-24	Longitude of the event in degrees to the nearest tenth
25	E or W for east or west longitude
26-28	Depth of event to the nearest kilometer
29-31	Magnitude to the nearest tenth
32-36	This is an output field. The program will compute the distance (to the nearest kilometer) between the event and the standard subarray (AO for LASA)
37-39	This is an output field. The program will compute the station to epicenter azimuth (to the nearest degree relative to AO).
40-78	Not used by the program, but reproduced on output.
79-80	Must be blank, to identify this card as an event card and not a phase card.

Each event card should be followed by phase cards. A phase card contains the observed phase data for a given subarray. Each phase card must have an index number punched in Columns of the subarray location cards (See Sec-C9). There does not have to be a phase card for every subarray location card nor a specific numerical order.

Phase Card Format:

FORMAT (Columns 1 through 9 contain the phase arrival time at this subarray)

COLS.	
1-2	Hour
3-4	Minute
5-9	Second to the nearest hundredth
10	Not Used
11-14	Amplitude (zero to peak) to the nearest millimicron
15-16	Not Used
17-20	Amplitude (peak to peak) to the nearest millimicron
21	Not Used
30	Signal Quality
31-35	Time anomaly to the nearest hundredth of a second -- this is an output item computed by the program.
36-40	Amplitude anomaly zero to peak relative to geometric mean computed by the program (output field)
41-42	Subarray name code (output item)
43	Not Used
44-45	Reference subarray (for each event) (only in last phase card)
46-50	Peak to peak amplitude anomaly relative to geometric mean (output field)
51-55	Zero to peak amplitude anomaly normalized to average amplitude (O-P) (output field)
56-60	Peak to peak amplitude anomaly normalized to average amplitude (P-P) (output field)
61-78	Reserved but not used by program
79-80	Index number of subarray recording this phase must correspond to subarray location card

Additional events with their associated phase cards follow in like fashion for as many events as desired. The subarray location cards are not repeated in the deck setup.

The output tape is a card image tape, with the same information and format as the input tape with the addition of the computed values for distance and azimuth for event cards, and travel-time and amplitude anomalies for the phase cards.

10. Selective Jump and Stop Settings: None

11. Timing: Approximately 3.5 seconds per event

12. Accuracy: No better than the input data

13. Cautions to User: Every phase card must have an index number. If Columns 79-80 are blank, the program assumes it is an event card

14. Equipment Configuration: Standard F-63 COOP monitor system with the card reader on Unit 7 and the printer on Unit 6 and the output tape on Unit 16.

15. References: Letter from MIT dated April 8, 1966

D. METHOD

Definitions

Observed Travel-Time = Observed Phase Arrival Time Minus Event Origin Time

Predicted Travel-Time = Travel-Time for the J-B Table. Found by table look-up on distance and depth with four-point interpolation for distance and linear interpolation for depth.

O_i = Observed travel-time at subarray i

H_i = Predicted travel-time to subarray i

O_r = Observed travel-time at standard subarray

H_r = Predicted travel-time to standard subarray

Transit Time Residual (Travel-Time Anomaly) = $O_i - O_r + H_r - H_i$

(Relative) Amplitude Anomaly = Amplitude (Zero to Peak) at subarray i divided by geometric mean amplitude (zero to peak)

(Average) Amplitude Anomaly = Amplitude (Zero to Peak) at subarray i divided by arithmetic average amplitude (zero to peak) for all functioning subarrays.

Relative and average amplitude anomalies are also computed in like manner for the peak to peak measurements.

APPENDIX C

SEISMIC DATA LABORATORY
ALEXANDRIA, VIRGINIA

DIGITAL COMPUTING SECTION

A. IDENTIFICATION

Title: Display and Analysis of Anomalies

COOP Identification: Z95 DISPLAY

Category: General

Programmer: J. W. Monroe

Date: 19 July 1966

B. PURPOSE

To take the output from the anomaly program and compute the average, standard deviation, and number of occurrences of a selected anomaly for selected subarrays or sensors, distances, and azimuths.

C. USAGE

1. Operational Procedure: This FORTRAN-63 program is with a binary or symbolic deck and a set of control cards for each use.
2. Parameters: None
3. Space Required: 21,222 buffers
4. Temporary Storage Requirement: None
5. Print-Outs: The program first prints out the anomaly used, followed by the distance and azimuth criteria and the subarrays or sensors used. If any seismograms are to be deleted from processing, they are listed next. Following this will be a page for each subarray or sensor with the average, standard deviation and number of occurrences of the selected anomaly for each distance and azimuth chosen. If plotting is requested, the last page will contain scale factors and other information pertaining to the plots.

6. Error Returns: None

7. Error Stops: None

8. Input and Output Tape Mountings:

    Logical Unit #4 - Input BCD tape from ANOMALY

    Logical Unit #3 - Output plot tape if desired

9. Input and Output Formats:

INPUT: (only one case per run)

Card #	Cols	Format	Description
1	1	I1	Anomaly to be used (see last page)
	5	I1	Plot switch 1-plot, blank-no plot
2	1-10	I10	Number of Dels (Max 19)
	11-20	I10	Number of Azimuths (Max 13)
	21-30	I10	Number of Subarrays or Sensors (Max 21)
next N	1-10	F10.2	Distance (km)
	11-20	F10.2	$\pm$ Distance (km)
Where N = NO.	Punched in Cols 1-10 on card #2 (Max 19)		
next M	1-10	F10.2	Azimuth (Deg)
	11-20	F10.2	$\pm$ Azimuth (Deg)
Where M = NO.	punched in Cols 11-20 on card #2 (Max 13)		
next L	1-10	F10.0	Subarray or Sensor Number
Where L = NO.	punched in Cols 21-30 on card #2 (Max 21)		
next D	1-4	I4	Seismogram Nos. to be deleted (Max 100)

OUTPUT: The printed output will be that described in PRINT-OUTS. The plot tape on logical unit #3 will contain a plot for each subarray or sensor of the average for that subarray minus the average of averages for all subarrays. The plotted values will be computed for each distance at each azimuth (in that order) until N points have been plotted where N equals the number of dels times the number of azimuths. The plots will always represent a new del every tenth of an inch.

10. Selective Jump and Stop Settings: None

11. Timing: 2 milli-sec per case where each case has a separate distance, azimuth, subarray, and anomaly.

12. Accuracy: The same as input data

13. Cautions to Users: Both logical units 3 and 4 must be mentioned in the COOP card. If no plot is desired, use the BY3 convention. The plot routine is not internally controlled so the user must request the same number of files to be plotted as there are subarrays or sensors with a maximum of ten across the plot. Observe that there are maximum limits on the number of distance and azimuth intervals and number of subarrays and seismograms to be deleted.

14. Equipment Configuration: Standard COOP for FORTRAN-63

15. References:

Program write-up for ANOMALY Fletcher 16 June 1966

D. METHOD

Average $= \bar{X}_{i,j,k} = \frac{1}{N_{i,j}} \sum X_{i,j,k}$

Standard Deviation $= \sigma_{i,j,k} = \frac{\left[\sum X^2_{i,j,k} - \left(\sum X_{i,j,k} \right)^2 / N_{i,j} \right]}{N_{i,j} - 1}$

Number of Occurrences $= N_{i,j,k}$

where, i = azimuth $\pm$ deg's

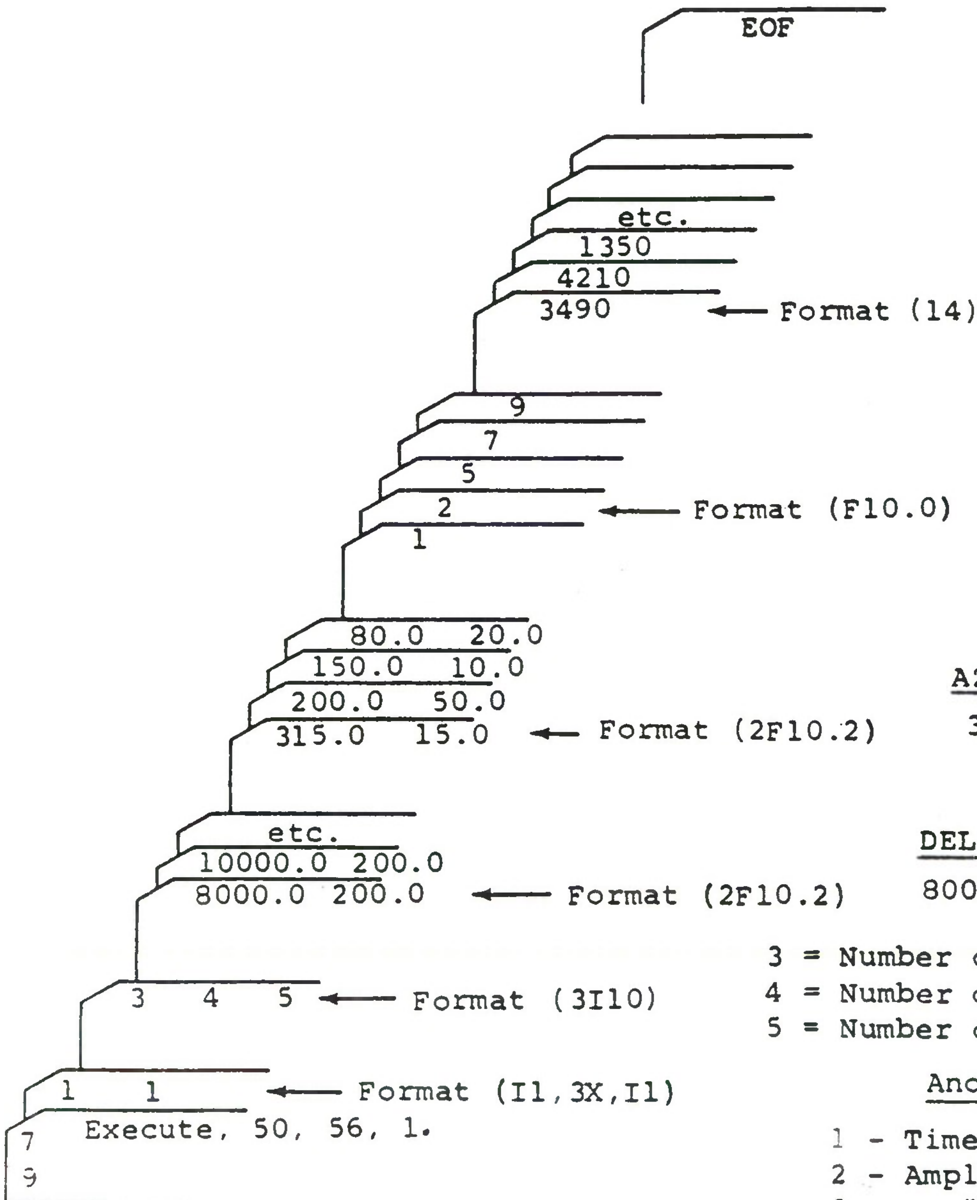
j = distance $\pm$ km's

k = subarray or sensor

N = number events pertinent to the specified coordinates and specified subarray

$X_{i,j,k}$ = anomaly used

SAMPLE INPUT DATA FOR DISPLAY



Event nos. punched on cards (1 per card) shall not be processed Max (100)

<u>Subarray No.</u>

<u>AZI Intervals</u>

315 $\pm$ 15 Deg

<u>DEL Intervals</u>

8000 $\pm$ 200 km

3 = Number of Del Intervals - Max(19)
4 = Number of Azi Intervals - Max(13)
5 = Number of Subarrays or Sensors - Max(21)

<u>Anomaly To Be Used</u>

1 - Time
2 - Amplitude (Z - P) Relative
3 - " (P - P) "
4 - " (Z - P) Average
5 - " (P - P) "

<u>Plot Switch</u> (col no. 5)

blank - no plot
1 - plot desired

TO: Users of Program DISPLAY

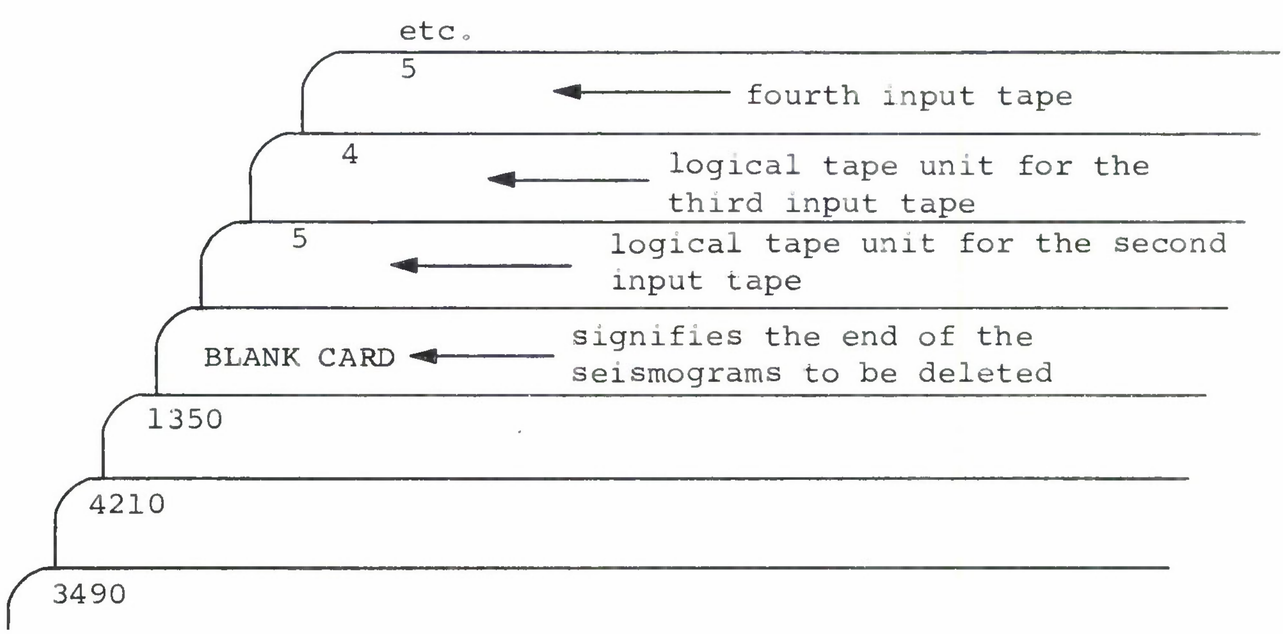
FROM: J. W. Monroe

DATE: 2 September 1966

SUBJECT: Additional Features of Program DISPLAY

REFERENCE: Z95 DISPLAY Program Writeup, 19 July 1966

The user may now run DISPLAY using more than one input tape described in the program writeup referenced above. The first input tape <u>must</u> be on Logical Unit 4 but the second, third, etc., tapes may be assigned to any logical unit from 1 thru 49 inclusive, except Logical Unit 3 (the plot tape). When using more than one input tape, Logical Units 3,4, and all other logical units must be mentioned in the COOP card. The control card setup for the case of more than one input tape is exactly the same as that shown in the SAMPLE INPUT DATA FOR <u>DISPLAY</u> of the writeup, except that following the last card of seismograms to be deleted or following the last subarray number if there are no deletion cards, a blank card must be inserted followed by the logical tape assignment for the <u>second</u> input tape. If more than two input tapes are used, additional cards are used to specify the logical tape unit for input tapes 3,4, etc., but the blank card is not used again. Format for these tape assignments is I5. The following is a sample card setup starting with the deletion cards:



As soon as an end of file is encountered on the input tape being processed, a tape assignment card is read in and the program pauses with the next input logical unit number displayed in the "A" register. When the Start Key is hit, the program begins processing the new input tape. Two input tape units might be used, such as 4 and 5 where the first tape is on Unit 4 and the second tape is mounted on 5 while 4 is being processed. After Unit 5 begins processing, another tape could be mounted on Unit 4.

DEBUGGING AIDS FOR DISPLAY

Jump Key 2 — On displays the event number being processed in octal in the "A" register. Program halts until Start Key is hit. For exact stops, leave JK-2 on and step through events with Start Key. Program halts on header card of event being displayed in "A" register.

Jump Key 1
Jump Key 3 — Up causes printout of accumulation that far into the program. Turn JK-1 off as soon as printout begins and JK-3 off as soon as printout has finished. Use this feature sparingly since some loss of accuracy occurs when sigma is set equal to zero rather than a negative number. All other times, the accumulation is reset to its original value without loss of accuracy.

Be sure both COOP card and EXECUTE card have sufficient time limits for the case being run. For a case of 324 events with 21 stations, 17 distances, and 12 azimuths, allow at least 60 minutes.

CHANGE IN FORMAT

The format of the control cards containing the numbers of seismograms to be deleted has been changed from I4 to I5.

APPENDIX D

The product error model described in Appendix A can be used to detect amplitude data which is inconsistent with the population from which it is drawn. Several approaches to automating this error detection were suggested and the following is a description of the method which was finally selected for production use.

The collection of recorded data was grouped into a set of cells. The grouping geographically was by distance and azimuth and a cell is defined by a particular distance and azimuth range and a station designation. The assumptions made were that the geographic regions chosen are sufficiently small so that the true anomalies are constant within each region and that the variability is the same for all cells.

Using the results of Appendix A, namely that $\log e_{ij} \sim N(0, \sigma^2)$, one may make estimates, denoted as s^2, of σ^2 for each cell. These can be pooled to obtain a very good estimate of σ^2, and with this estimate and known distribution, outlying estimates and thus probably blunders can be detected.

The estimates of σ^2, computed for each cell (given station j and region) are

$$s^2 = \frac{1}{I-1} \left[\sum_{1}^{I} X_i^2 - I_\mu^2 \right]$$

where I is the number of events recorded in the particular cell,

$$X_i = \log \frac{L_{ij}}{\left(\prod_{j=1}^{J} L_{ij}\right)^{1/J}}$$

$$\mu = \frac{1}{I} \sum_{1}^{I} X_i$$

and S^2 is distributed as χ^2_{I-1}.

By pooling these variance estimates, a very good overall estimate is obtained due to the large number of data. The estimates in each geographical cell were quantized, indexed and entered on a histogram, (Figure 6 of the main report) as a function of the number of events in that cell.

A pooled estimate of the population variance is then given by

$$\bar{S}^2 = \left[\sum_{I=2}^{\infty} \sum_{J=0}^{\infty} f_{I,j} \, S_j^2 \right] \Big/ \left[\sum_{I=2}^{\infty} \sum_{J=0}^{\infty} f_{I,j} \right]$$

where $f_{I,j}$ is the number of estimates in the class interval indexed by j and with I-events in the cells. The value of S_j^2 is equal to the center value of the variance in the class interval, j.

Using this estimate for σ^2 we may compute 100(1-α)% confidence intervals for S_N^2 and S_N. Thus, we set $\sigma^2 = \overline{S^2}$ and define confidence intervals.

$$\left(\frac{\sigma^2}{f}\right) \chi^2_{(\alpha/2,f)} < S_N^2 < \left(\frac{\sigma^2}{f}\right) \chi^2_{(1-\alpha/2,f)}$$

or

$$\left[\frac{\chi^2_{(\alpha/2,f)}}{f}\right]^{\frac{1}{2}} \sigma < S_N < \left[\frac{\chi^2_{(1-\alpha/2,f}}{}\right]^{\frac{1}{2}} \sigma$$

where f = number of degrees of freedom, (I - 1), and $\chi^2_{(\alpha/2,f)}$ and $\chi^2_{(1-\alpha/2,f)}$ are found in tables.

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13. ABSTRACT

Average amplitude anomalies are presented as functions of source region. Data from approximately 300 events were used in this analysis.

14. KEY WORDS

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